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ENERGY INNOVATION
FOR A SUSTAINABLE ECONOMY

11th-13th February 2020 The Park, Hyderabad, India

PAPER PROCEEDINGS

Organisers

Alliance for an Energy Efficient Economy

MacArthur Foundation

ACEEE American Council for an Energy-Efficient Economy

Co-Organisers

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DEPARTMENT OF SCIENCE & TECHNOLOGY
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Ministry of Power, Government of India

NITI Aayog

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Alliance for an Energy Efficient Economy (AEEE)
37 Link Road, Ground Floor, Lajpat Nagar III
New Delhi, 110 024
Tel: +91-11-41235600
Email: info@aeee.in
Website: www.aeee.in

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Foreword

India's energy consumption, driven by economic growth, a large and growing population, and rapid urbanization, is expected to grow faster than that of any other major economy in the world. Concurrently, India is also transitioning to a sustainable energy future amidst international commitments like the Paris Agreement (2015), the Kigali Amendment to the Montreal Protocol (2016) and Sustainable Development Goals 2030. Energy efficiency can emerge as a low-cost mediator between the drive towards economic maximization and environmental sustainability.

To realize this pressing need in the wake of a global climate emergency, it is important to create policy frameworks supported by evidence-based and data-driven research and development - this is where Alliance for an Energy Efficient Economy (AEEE) steps in. AEEE has emerged as a credible platform to foster a culture of energy efficiency in India by engaging the triple-sector leadership approach. AEEE works across different levels of stakeholders in the public sector, the private sector, and civil society. We stay committed to our mission with Energise 2020: *Energy Innovation for a Sustainable Economy*.

Energise is India's signature biennial conclave that convenes torchbearers of energy efficiency and sustainability from a diverse group of stakeholders including, the government, industry, civil society, and academia. It is the second of two editions of such conferences – INSPIRE 2017 was the first edition. Participants will gather at this pre-eminent meeting to discuss the technological basis for, and the practical implementation of actions to reduce the energy use and climate impacts associated with a wide range of sectors like buildings, manufacturing, agriculture, and transport. Energise, will further enable the sharing of ideas and engaging in dialogue with global leading thinkers, leaders and luminaries in the field. This will be executed through moderated panel discussions, keynote speeches, industry exhibitions, and paper presentations through three days. This electronic document includes all the technical papers presented during this conference. The papers cover the depth and breadth of the energy efficiency landscape – space cooling, electric mobility, energy performance measurement, and data analytics to name a few.

Bringing out credible research in the public domain can have a tremendous influence on effective policymaking and scaling business innovation. Therefore, the conveners have been careful to use a double-blind peer review process to curate the papers presented in the conference, as was done previously at INSPIRE in 2017. Such a state-of-the-art review process for selecting research papers in conferences in the Indian milieu has raised the bar for producing research on pressing policy and market questions. The conveners hope that the energy efficiency community finds this compilation of papers enriching and useful in their technical projects, and policy and business decisions.

Over 150 abstracts were received in mid-2019, from which 52 papers have been published in this electronic document to advance the discourse on energy efficiency in India and close knowledge gaps. The technical papers in this proceeding have been organized under three sections – Buildings and Communities, Energy Efficiency for Business Competitiveness and Urban Infrastructure and Utilities representing the three thematic tracks under which the whole set of technical papers were requested and evaluated. The peer-review effort was led by 38 technical committee members including four senior advisors and nine panel leaders comprising leading national and international experts from academia, policy think-tanks, and foundations, consulting, and the industry, representing the three thematic areas, to lend a balanced perspective to the whole process. Despite our best efforts, there might be some inconsistencies in the formatting of this document, considering the papers have been sourced from multiple authors – however, the technical information is accurate (to the best of the conveners' knowledge) and best attributed to the authors.

The conveners are delighted to present this electronic proceeding, which captures the research produced for Energise 2020.

Satish Kumar.

Satish Kumar, Ph.D. and LEED Fellow
Energise Convener
President & Executive Director, AEEE

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ENERGY EFFICIENCY FOR BUSINESS COMPETITIVENESS

URBAN INFRASTRUCTURE & UTILITIES

BUILDINGS & COMMUNITIES

DEVELOPMENT OF SIMULATION DATA VISUALIZATION FRAMEWORK FOR HIGH-PERFORMANCE BUILDINGS

Yashima Jain[1], Prasad Vaidya[2], Dr. Saket Sarraf[3]

[1]*Techincal Specialist,*
Green Business Certification Inc.
NOIDA, India
yashima120@gmail.com

[2]*Director,*
Solar Decathlon India,
Mumbai, India
prasad.vaidya@gmail.com

[3]*Principal,*
ps Collective
Ahmedabad, India
saket.sarraf@gmail.com

ABSTRACT

The output results from simulation tools are mainly alpha-numeric charts that are difficult to use and interpret for an architect. Poor data plotting limits the ability to compare, analyze and explore in depth, and thus leads to weak decision making.

This research is an attempt to bridge the communication gap between architects and energy modelers with energy information simulation results represented spatially. This study includes a robust literature review of data representation theory and past work in the representation of simulation results. The literature suggests that existing fragmented efforts need to be organized based on design stages and design disciplines. The methodology further includes interviews with practitioners, analysis of current state-of-the-art spatial representations, selection of metrics, and developing the representations for a test case building.

A theoretical framework for representation which can be followed to represent energy simulation data to architects has also been proposed. This framework is a combination of representation of design options along the x-axis, floors of the building along the y-axis and representation of data for various metrics along z-axis. This provides consistency in the representations as well as the use of the building 3-D models as a background map that architects are familiar with, and it enables comparison of the options. The results show that such representations can lead to a better understanding of the relationship between the building elements and building performance. They also show that certain metrics are more useful to stakeholders and combination or overlays of such metrics can lead to better understanding of design performance.

Keywords—Design decision making, energy simulation data results, spatial representations, representation framework, output metrics

INTRODUCTION

The development of building simulation programs has resulted in high levels of modelling capabilities in the last two decades. This has enabled energy simulation experts to provide architects and designers with information to aid decision making where they previously relied on intuition, experience, simplified calculations and rules of thumb (Morbitzer, Strachan, Webster, Spires, & Cafferty, 2001).

However, feedback from simulations has not been fully integrated into the design process (Morbitzer et al., 2001). Lawson (1990) identified that building design has moved from a mere 'craft-based approach' to a process that involves advanced technologies. This can be linked to the view that simulation should not only be used for final performance confirmation but as an integrated element of the design process (Augenbroe, 1992). The building design community has been challenged by continuously increasing energy demand, along with ambitious goals for improved indoor environment, reducing environmental impacts, and reducing building costs. Although various energy simulation programs have emerged in recent years, few of them paid attention to visualization of simulation results, which is critical to communicate building performance information to architects (Y. Chen, Liang, & Hong, 2017).

The development of building simulation programs has also led to an increase in the availability of building energy simulation data in the past one decade. But a similar trend has not been seen in the research and development (R & D) of data visualization in the building energy sector. Keyword searches in the scientific database "ScienceDirect" shows that in the past decade research information on *data driven decision making* has increased by 14% whereas that on *data visualization* has increased by 4% only. Clearly, the latter has received less attention and needs to be delved into for better understanding and informed decision making.

LITERATURE REVIEW

Data Visualization Theory

Data visualization is the representation of quantitative information to help people make sense of complex phenomena. With knowledge expanding by the nanosecond, information anxiety is created by the gap between what we understand and what we think we should understand (Cairo, 2012).

Components of data visualization

According to Kirk (2016), data, representation, presentation, and understanding are the four components of data visualization. Wilkinson (2005) and Bertin (2011) later identified six visual cues and ranked them based on graphical perception, namely: position, length, angle, direction, area, volume, saturation and hue.

Principles of data visualization

Graphics provide an excellent approach for exploring data and are useful for presenting results. Kirk (2012) elaborated that storytelling is one method to achieve understanding through visualization, but stories can emerge in various directions, whereas story-forming is another method where interpretation and comprehension is left on the user. Kirk (2016) identified three high level principles that help in answering the question: *"Is my visualization good visualization design?"* (**Error!**

Figure 1 The three principles of good visualization design

Reference source not found.*)*

Cairo (2012) described the core principle of any data visualization to be able to tell a story clearly by achieving order and having a narrative through each graphic. He mentioned that even though the methods of work might have been used in the past 40-50 years, but any project should always start by analysing what the story is about and then find the best way to tell it by splitting it up into easily digestible chunks, without losing depth.

Communication of complex energy simulation data

Energy simulation related data and tools

With an increase in the awareness for the need of energy-efficient buildings, there has been an increase in the number of energy simulation tools available, either free or for a fee. Currently, there are 606 tools listed on the U.S. Department of Energy (DOE) Building Energy Software Tools Directory (BEST-D) website ("Building Energy Software Tools Directory," 2014). Wilson & Merket (2018) stated that any energy model has approximately 100 building characteristics parameters associated with them. They further elaborated that simulation results have around 30 metrics, including annual energy use disaggregated by fuel type and end-use category, as well as calculated energy use, utility bills, and carbon emissions which was calculated to be over 4 billion data points. This amount of data becomes unmanageable to work with.

Typical energy modelling programs are often complex for architects to use, especially during the early stages of design, resulting in building energy simulations being performed at later stages of design process (Schlueter & Thesseling, 2009). Paryudi (2015) mentioned that architects are novices in the energy simulation field, therefore they lack simulation know-how. This weakness impedes architects from using existing energy simulation tools regularly. Because of that, most architects prefer simple energy simulation tools which offer features to allow them to model quickly and explore alternative scenarios.

Spatial and temporal representations

Data produced by various energy simulation software is enormous and becomes unmanageable to understand for an architect if presented as tables or reams of numbers (Wilson & Merket, 2018). They suggested that spatial representations can facilitate visualization of large-scale building energy simulation results. Spatial data communication is important to enable intuitive understanding of design performance. When communicating the results of environment and building performance analysis, it is important to display resultant information in order to be (1) holistically understood and (2) guide architectural design decisions.

Several attempts have been made to integrate architectural performance data displays to improve the understanding of the performance of a design. Prazeres & Clarke (2003) proposed a dashboard for many related performance metrics, but the results were only tabulated next to an image of the computational model rather than associated with it. Reinhart & Wienold (2011) proposed a dashboard view of simulation results that provides comprehensive information for a single-space "shoebox" model which focused on the impacts of daylighting on energy use in perimeter spaces and cannot be easily extended to entire buildings. Jakubiec (2017) provides an overview of a schema to display and relate multiple spatial building performance metrics for passive design analysis. Metrics like DA300 lux and UDIe>3,000 lux hybrid for daylighting analysis, thermal comfort autonomy, and average air change per hour (ACH) were chosen to assess major environmental quality factors that are spatially discrete and therefore help designers to understand the relationship between formal design and environmental performance.

The choice and presentation of performance metrics have a significant impact on our understanding of the total performance of a design and the factors that lead to that performance. A study by Mackey (2015) looked at an approach to design with the thermal environment, attempting to communicate to users a spatial map that

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suggests why a certain architectural layout leads to a certain type of thermal performance. Venancio, Pedrini, Linden, Ham, & Stouffs (2011) suggest that to connect building performance simulation outputs to "designerly" understanding and thought processes, performance metrics must be synthesized in a way that can address specific design dilemmas such as internal layout, shading devices, openings, finishes, and material selections. Marsh (2004), in an early paper on the Ecotect software suggested that only by achieving understanding in a designerly way can environmental analysis drive a design process. "Project STASIO" (2018) also aims to guide on how to effectively apply building energy modelling at an energy design stage for effective communication of simulation inputs and outputs between the designer and the energy analyst.

Integrating energy analysis with design stages

With energy efficiency gaining its importance, architects want to narrow down design alternatives to those that are more promising to save energy (Zarrinmehr, 2015). Dahl, (2005) showed that decisions made early in a project have a strong effect on energy savings and life cycle costs of a building. It is important to determine various architectural design stages to have inputs in simulations at all design stages and establish a holistic design approach (Morbitzer et al., 2001). Sinclair (2013) has identified three main building design phases, (1) Outline design stage (2) Scheme design stage (3) Detailed design stage (RIBA, 2013). American Institute of Architects (AIA, 2012) has also endorsed similar design stages with important areas to be investigated during energy modelling process. Chartered Institution of Building Services Engineers CIBSE (1998) also identifies this as a good practice strategy for design decisions to ensure energy efficient building design.

All strategies within the planning phase affect the solar access, wind access and daylight autonomy metrics. All strategies within the planning phase and building performance phase affect the EUI and daylight autonomy metrics. Finally, all strategies within the planning phase, building performance phase and energy source phase affect the carbon emissions metric. Project teams which optimize the design aspects of building shape, orientation, configuration, envelope, and daylighting can design a building that requires less energy and smaller mechanical systems (Stumpf, Kim, & Jenicek, 2011).

Summary

The role of a visualization is to allow the human brain to establish a connection between an observed a phenomenon and related data, and to generate meaning. Storytelling is an important aspect to connection a users' interrogation and her interpretation when reading a visualization design. This is effectively done by splitting data into digestible and understandable chunks of information without losing its depth.

Visualize of energy simulation data produced by available tools in the market today is unmanageable, and not relatable to building elements and features for architects. Spatial and temporal representation are important modes that enable intuitive understanding of design performance. Past work on representations for architects needs organization by design stages. Input parameters and results metrics need to be identified for these design stages.

METHODOLOGY

Interviews

This step involved preparation of an interview outline, preparing a list of suitable interviewees, conducting the interviews and analysing them. The aim was to (1) collect personal experiences to understand the problems faced by architects and energy consultants while communicating energy simulation results or needs, and (2) to help select existing representations to be analysed further within this study. The interviews included discussion on the metrics that they would prefer using in their presentations. Mock-ups of representation examples were added to show the difference between typical simulation results viewed with single summary metrics such as EUI, and representations that we identified as 'designerly'. Five architects and four energy consultants were interviewed.

A qualitative analysis of the transcribed interviews was done based on the following 4 broad aspects: use of energy simulations; problems in communicating energy simulation results; type of representations used, and; the choice of metrics. Common findings from the interviews were listed. Further, the results from the interviews were compared with the literature review and comments that support or conflict with the literature were identified. A framework for the classification of representations was formulated based on this analysis. See section 4 for the framework questions.

Classification of existing representations

80 spatial or temporal representations of energy simulation data were collected from various research papers like Jakubiec, 2017, Fonseca, 2015, and M. Doelling, 2012 and online portals like "Project StaSIO," 2018 and "Hydra - Sharing made easy".

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Classification and evaluation of representations

Based on literature review and interviews, a list of design decisions taken by architects at various design stages was made and classification of the representations was done. A matrix of output metrics and design decisions in the representations studied for the concept design stage and preliminary design stage was made (*Figure 2*).

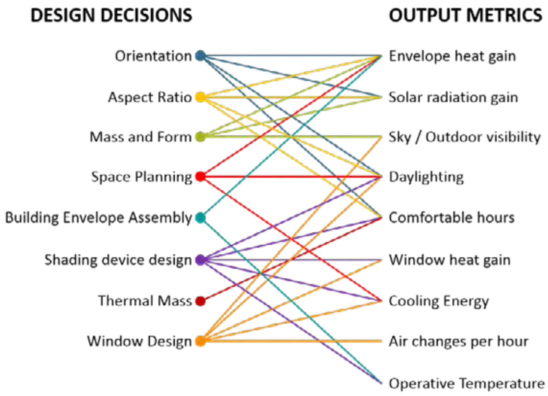

Figure 2 Design decisions and corresponding metrics in a concept design stage

Each representation was evaluated for the questions in the framework and scored. ***Figure 3*** shows an example of how the color-coded scoring was done for each representation. Some representations addressed more than one design decision and the resulting arrangement formed a Venn diagram of design decisions. ***Figure 4*** is an example of this Venn diagram of representations with overlapping design decisions.

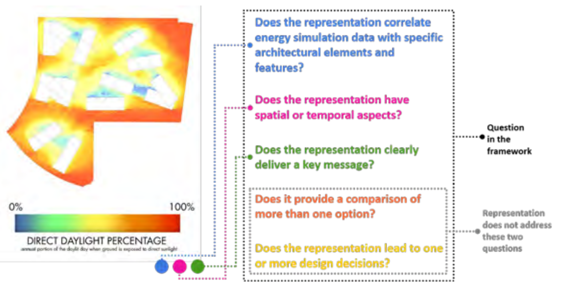

Figure 3 Example of color-coded scoring of representations

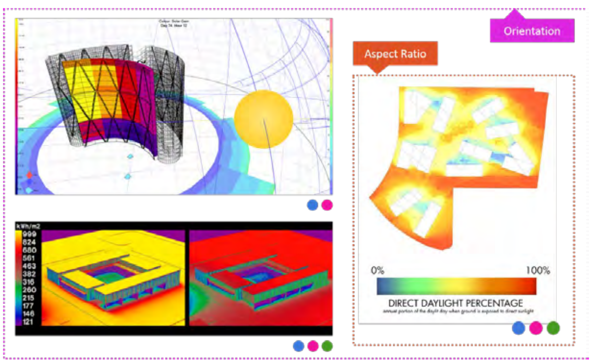

Figure 4 Mock-up of grouping of representations with overlapping design decisions

Identification of the representation gap

The representations which do not exist were identified. A matrix of design decisions and framework questions was colour coded to identify the representations that need to be modified. A combined list of design decisions with its corresponding metric was formed which either need to be modified or made from the beginning.

Demonstration of representations

To develop representations of simulation results, a building that had been simulated previously on a real project, and that had less 50 thermal zones was selected for modelling. The building geometry was made in Rhino v6 and imported to Grasshopper. Simulaton inputs parameters for building characteristics and operation were based on information provided by the project team. The representations were produced based on the various output metrics for the concept design stage. The output from this step were representations which represented data on a spatial axis and followed a consistent visualization framework.

ANALYSIS AND RESULTS

Interviews

About using energy simulations

Most of the interviewees reported that graphical representation of energy simulation data is key to better communication, enhanced understanding and decision making for architects. Energy consultants in the interview reported that architects prefer not to involve them in the early design stages and prefer to use in-house techniques and their own intuitive understanding. This suggests that it is important to make representations that are easy to prepare for energy consultants and are easily understandable for architects. Architects reported a disconnect between energy simulation results and design philosophies. This connection can be built or reinforced by providing representations that can support design philosophy of architects. Energy consultants reported the importance of energy simulation results as well as the need for representations to aide communication with architects. It can be inferred that good representations of simulation data are important if they need to inform or reinforce the design philosophy.

About problems in communicating energy simulation results

Many interviewees reported that it is a challenge to aid early design decision-making for architects using metrics such as final energy at the building level. Energy consultants should choose input parameters and output metrics that are appropriate to the design stages for better acceptance of data. Architects suggested that energy modelling results should not only identify problems but also suggest and evaluate potential solutions to the problems. A comparative analysis of options could be helpful for this. Also, at an early design stage, an architect wants to switch quickly between design options based on the simulation results provided. Ostergard, Jensen and Maagaard recognized the issue of time-consuming, iterative and evaluative nature of building simulation. The major concern is the level of precision used in the energy model for design stages. Attia, 2012 used the concept of pre-design informative building performance simulation which used data from meta-models in early design stages.

About types of representations

All architects reported that the typical graphical representations of energy simulation data produced as Excel graphs do not suffice and there is a need for other representation methods. The representations should help an architect in design decisions and not be limited in reporting on the efficiency of the building.

Most of the architects as well as energy consultants agreed that spatial representations were useful for better communication and decision making. Architects reported that spatialization of simulation results is valuable because it helps to relate the results to building elements and features. Jakubiec, 2017 also explored a method for analysis of building performance results spatially which helped in establishing a relationship between form and environmental outcomes as well as synergies between different metrics. Energy consultants mentioned that design teams need a key take-away from representations like graphs, charts or tables. This supports the use of a representation which can give a direct message to the architect rather than only providing exploratory graphics that need time to understand and can also be interpreted differently by different people.

About choice of Metrics

Architects reported that energy consultants tend to use energy jargon which becomes technical and hinders their understanding and decision-making. They suggested that energy consultants need to use output metrics that are appropriate for the early design stages and which can aid the design philosophy and eventually impact the design decisions in any project. Jakubiec, Doelling and Heckmann, 2017 have also mentioned that the mode of communication in many graphical user interfaces (GUI's) focus on final energy of the whole building or a single thermal zone. The flow of heat, air and light, which may be more related to the building elements being designed is difficult to understand using numerical, tabular or charted outputs that show bar, column, pie, histogram and scatterplot outputs. Architects reported that metrics focusing on comfort are the most vital, and spatial representation can have a major impact on their decision making.

Based on this analysis, a framework of questions was prepared to analyse the current state of the art representations. The questions in the framework are as mentioned in ***Figure 3***.

Classification of design decisions and corresponding metrics

This section identifies and classifies various design decisions and the corresponding metrics that need to be analysed to propose an energy efficient building design. This was done for three design stages which are pre-design stage, concept stage and preliminary design stage.

Pre-design Stage

As per CIBSE (1998), functional, technical and financial feasibility is checked in this stage. From a building energy efficiency standpoint, climate analysis is done which involves analysis of the outdoor conditions based on the weather file of the city. According to AIA (2012), no architectural design decisions are made in the pre-design stage. Analysis done in this stage is used to inform design strategies and energy efficiency measures that may be incorporated in the design in later stages. Questions were formulated which should be investigated to aid decision making.

- What are the ranges for seasonal or diurnal temperature and relative humidity?
- What are is the frequency distribution of wind speed and direction?
- What is the diurnal variation in temperature?
- What are the hours when the ambient conditions provide comfort without implementation of any strategy?
- What are the solar angles for times of the year that require heating or cooling?
- What are the performance targets?
- What energy conservation measures (ECMs) are required by law or applicable energy codes?
- What ECMs may by required based on the project goals for performance or green building rating?

Concept Design Stage

The decisions made in the concept design stage are crucial since they have the highest potential for improving the building's energy performance. The responses from architects in the interviews focused on developing a clear design strategy that integrates fabric, services and human factors. The responses from energy consultants in the interviews stated that they look at solar insolation, heat flux through the envelope, operative or air temperature, comfortable hours, cooling/heating load and daylighting metrics to support these design decisions (***Figure 5***). On a summary level, metrics like target for annual energy use (Energy Use Intensity in kWh/m^2/year), a percentage reduction below a certain baseline (e.g. 40% below an ECBC baseline), or specific strategies (e.g. no mechanical cooling) should also be studied to drive the design

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decisions. The answers to the following questions should be investigated and analysed to aid decision making for architects.

- What should be the orientation and dimensions of the building to minimize heat gain, maximize daylight & natural ventilation through building envelop?
- What should be the window area or window to wall ratio (WWR) for different directions to minimize heat gain and maximizing daylighting?
- How should interior space use be zoned for higher performance of the building?
- What kind of shading devices minimize direct solar radiation and glare through fenestration?
- Which passive strategy can be employed to reduce heat gains to make the building thermally comfortable without any additional energy consumption?
- What systems shall be used to harness maximum amount of daylight?

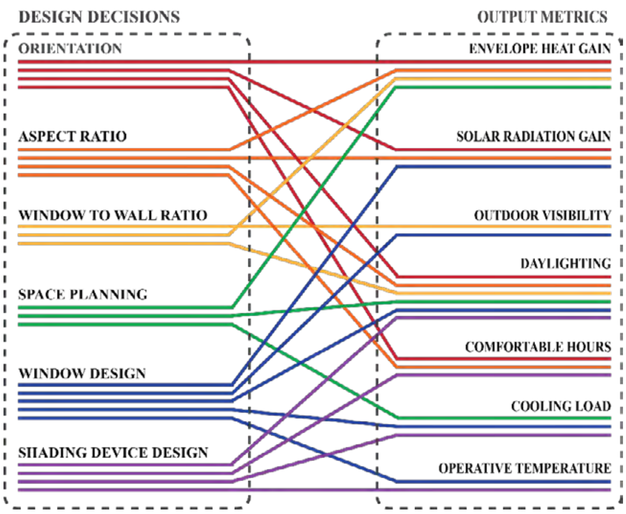

Figure 5 Design decisions and corresponding metrics for concept design stage

Preliminary Design Stage

In this stage, the architect develops the design to include proposals for structural design, building services systems, outline specifications, and cost estimates in accordance with the design programme (CIBSE, 1998). The energy modeller prepares a more detailed energy model and evaluates various combinations of energy saving features. The difference between the models in concept design and the preliminary design is the detail available about the building design. Apart from the metrics mentioned in the concept design stage, financial metrics like net present value (NPV), return on investment (ROI) can add value to the decision-making criteria (RIBA, 2013). This analysis could be iterative and should evaluate the potential to size correctly or eliminate building systems, ensure compliance with performance goals, and evaluate options with a comprehensive life cycle cost analysis (LCCA). The answers to the following questions should be investigated and analysed to aid decision making for architects.

- Which building envelope assembly for wall, roof, window will optimize comfort and energy efficiency? Would thermal mass be advantageous?
- What should be lighting power density (LPD) for various zones? How lighting control can be done for optimizing energy consumption to meet required lighting levels?
- What would be the effect of using occupancy sensors and daylighting sensors in various spaces?
- What type of HVAC system will be required? What would be the sizing of the system to meet the requirements?
- How can HVAC controls be used to reduce energy consumption?

Analysis of the relationship between design decisions and output metrics

The above classification was based on the feedback from the interviews and the literature review. It can be argued that each design decision can be represented using any metric and need not be limited to the above classification. These metrics that architects would be interested in, can be conceived along a flow of energy from the exterior environment to the interior that finally results in a perceived or measured system impacts *(*Figure *6)*. This flow, if divided into four broad stages can help us categorize the metrics as:

1. In the Environment – Solar Insolation
2. At the Envelope – Heat Flux (through the envelope)
3. In the Space – Indoor space temperature (Operative Temperature. Air Temperature, etc.)
4. System Impact – Envelope Load, Cooling Load, Energy Use Intensity, Comfortable Hours

The interviews showed that energy consultants tend to focus on systems impact metrics whereas an architect's interest lies in the environmental, envelope and space metrics.

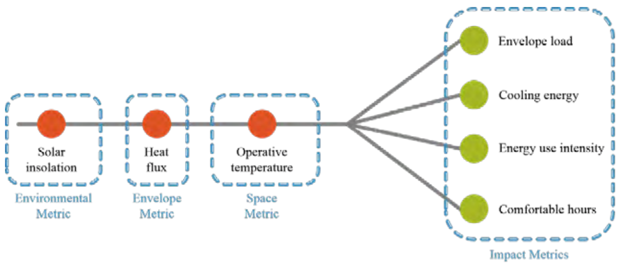

Figure 6 Flow of output metrics

Classification of representations

This section evaluates the current state-of-the-art representations based on the questions and the design decisions listed for various design stages. Based on the classification, a matrix of the current availability and the response to the questions was prepared for each design stage.

Pre-design Stage

Representations related to climate and site analysis were segregated and analyzed in this design stage. Eight representations from the entire set were a part of this design stage. Since, design decisions are not made in this design stage, representations were grouped based on the analysis done. Architects analyze the site context and climate in this design stage.

Concept Design Stage

All the representations related to orientation, aspect ratio, massing, space planning, building envelope assembly, window design and shading device design were evaluated in this stage. 24 representations needed to be developed. Some of these could be combined or overlaid.

Preliminary Design Stage

Some of the design decisions in the preliminary design stage are similar to those in the concept design stage, however, the detailing of the design increases with more specificity as the building design evolves further. For example, the architect prefers to look at heat transfer sections through various envelope assemblies and construction joints rather heat flux through the building envelope.

Proposed representations

This section discusses the representations proposed for the concept design stage. The following theoretical framework has been proposed for energy efficiency visualizations, based on the findings of this study.

The proposed representations shall:

- Enable exploration of the data to enable deeper understanding.
- Relate architectural design and features with energy simulation results.
- Compare among options to aid in decision making.
- Support decisions by providing summary results of key metrics.
- Use the spatial and/or temporal dimensions in the representations.
- Use consistent spatial visualization framework – an axonometric view with interior layout or a shoe-box model.
- Be sensitive to cognitive aspects of visualization like size, colour, scale, orientation, density, and line weights.

Each representation should have two elements. One element should highlight the key message with a summary metric. While, the second element would highlight the exploratory aspect of the visualization. This will enable the architects to make design decisions while allowing them to explore the visualization to relate simulation results further.

Energy simulation results should be represented spatially which are easier to relate to building elements and features. Representation of data on the surface should be chosen when representing surface-based results like energy flux, while representing data in an interior layout of axonometric view should be chosen to represent metric having an impact in the interiors like envelope load, indoor temperature, cooling load, etc.

The metrics that architects would be interested in, can be conceived along a flow of energy from the exterior environment to the interior that finally results in a perceived or measured system impacts. This included solar insolation (environmental metric), heat flux (envelope metric), indoor temperature (space metric) and envelope load, cooling load, energy use intensity and comfortable hours (impact metrics).

The use of colour also plays an important aspect. A monochromatic theme should be chosen when the aim is to understand the magnitude of the result. A colour theme ranging from warm to cool colours should be used when the comfort is the prime focus in the visualization.

DISCUSSION

This section reflects the identification and demonstration of various representations approaches in this research. Various methods were used to represent energy simulation results to aid decision making for architects. Metrics like solar insolation, heat flux, indoor temperature, envelope load and comfort hurs were used to represent simulation results. This paper discusses comfort hours as the representative metric to understand the evolution of the proposed framework and its sensitivity to the cognitive aspects of visualization.

Comfort hours is a representation of the hours a space is comfortable based on any thermal comfort model. It can also be further converted to percentage for better understanding. Initially, over-heated hours were represented on an axonometric view. This visualization only represented results for uncomfortable times and does not provide an overall comfort analysis for each space. Further, comfort hours were represented in terms of percent of occupied time where a point of space meets or exceeds a given set of thermal comfort acceptability criteria. Figure 7 represents the thermal comfort percentage at a 1m x 1m grid for each space. It is a 3-d exploded axonometric view of the four floors in building.

Two options, where one is the base case with 90% WWR and the other with 45% WWR have been represented.

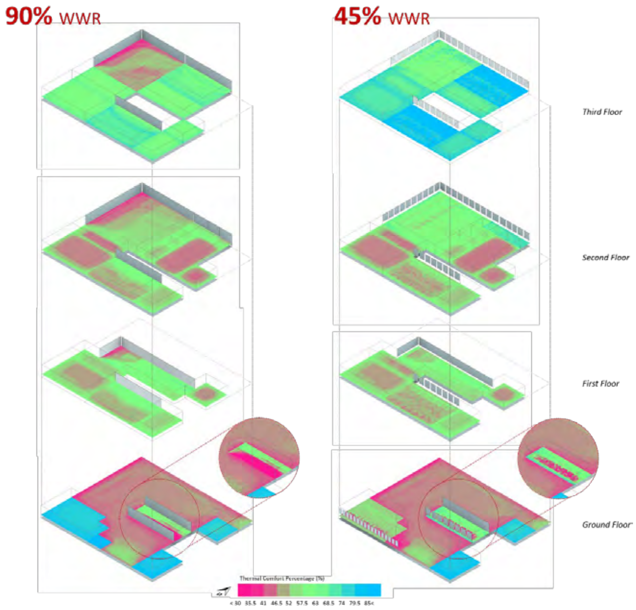

Figure 7 Thermal comfort percentage at 1m x 1m grid in each space for all the floors

The use of multi-level exploded axonometric for various floors in the building to show interiors and single exploded axonometric to show building surfaces proved to the most designerly and decisive in nature. Post processing of the results was done to arrange each isometric view to form an exploded view of the building.

Each representation was tweaked multiple times to achieve an outcome which addresses each question in the framework as well as would provide various decisions in the concept design stage. Since, output metrics are sequential due to the flow from outdoors to indoors, they can be chosen as a framework to represent data. The use of colour also proved to be essential since the human brain perceives colours in a certain way. The conclusion is a framework to represent energy simulation data results to architects.

CONCLUSIONS

This study found through literature review and interviews with practitioners that spatial representation proves to be an important mode of communication for intuitive understanding of building design performance. That better representation can lead to integration of energy simulation within the design process to aid decision making. The literature review indicated that there are fragmented efforts for better visualization of simulation data, but there is a need to organize these efforts and provide a conceptual framework.

In this study, spatial representations were developed for concept design stage which would aid in an informed decision making for architects. A classification of metrics was proposed which can facilitate design decisions like orientation, aspect ratio, window to wall area ratio (WWR), space planning, window design and shading device design. These metrics were identified from literature review, interviews of architects / energy consultants and analysis of current state-of-the-art representations. They are solar insolation (environmental metric), heat flux (envelope metric), indoor space temperature (space metric) and envelope load, cooling energy, energy use intensity and comfortable hours (impact metrics). Also, daylighting metrics like daylight autonomy (DA) and annual sun exposure (ASE) support the classification of the propose metrics which can be used for visualizations based on the design decision.

This study also proposes a framework which can be followed to represent energy simulation data to architects. The framework is a combination of representation of various options along x-axis, floors of the building along y-axis and representation of data for various metrics along the z-axis (***Figure 8***). This provides consistency in the representations, a background map that architects are familiar with so that data can be displayed for easy communication, and options can be compared.

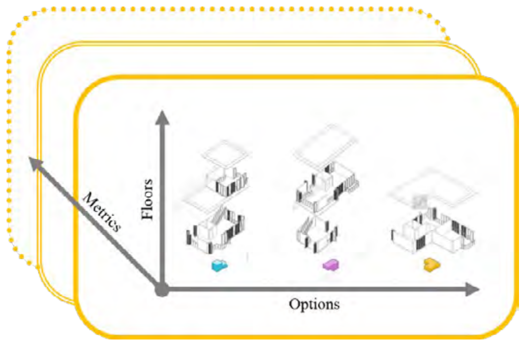

Figure 8 Schematic for framework of representation

Apart from this framework, each visualization should also:

- Enable exploration of the data to enable deeper understanding.
- Use the spatial and/or temporal dimensions in the representations.
- Use consistent spatial visualization framework – an axonometric view with interior layout or a shoe-box model.
- Relate architectural design and features with energy simulation results.
- Compare among options to aid in decision making.
- Support decisions by providing summary results of key metrics.
- Be sensitive to cognitive aspects of visualization like size, colour, scale, orientation, density, and line weights.

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BRIDGING THE GAP BETWEEN SIMULATED AND MEASURED DAYLIGHTING PERFORMANCE OF AN OFFICE SPACE

Jeevan Mohan[1] , Swati Puchalapalli[2]

[1]*Associate & Senior Consultant*
Terra Viridis Consultants LLP
Hyderabad, India
jeevan@terraviridis.co.uk

[2]*Director & Principal Consultant*
Terra Viridis Consultants LLP
Hyderabad, India
swati@terraviridis.co.uk

ABSTRACT

This paper seeks to illustrate the learnings from rigorous daylight simulations, illuminance data obtained from field measurents and visual comfort study over a span of 5 years for four office blocks in an IT campus, The Infosys Pocharam Campus's Software Development Blocks 2,3,4&5 in Hyderabad. This paper highlights how the client's objective to provide a glare free daylit open plan office without any internal blinds has been met across all the various buildings that were constructed in three phases. This paper provides an insight into correlating simulated performance vs actual measured performance and deriving appropriate workflow methodologies and better parameters for high performance buildings.

Initial validation studies were undertaken in late 2010 for the built project on campus using static Daylight measurement metric Daylight factor (DF). Simulations of as built case were compared against onsite measurements and key inferences were applied in the design of Identical blocks of SDB 2&3. In 2012, Post Occupancy evaluation and new set of validation studies was done to compare the design case vs as-built case vs actual onsite measurements. Further findings in term of 'influence of furniture geometry', material reflectance's, user perception of visual comfort in addition to Daylight illumination & Distribution became paramount for design of newer blocks SDB 4&5. In 2012-2013 CBDM (Climate based daylight modelling) was used and metrics like Daylight Autonomy (DA) & Useful Daylight Index (UDI) was used to make informed design decisions. Post occupancy validation study was undertaken to evaluate the daylight performance of the space.

Keywords— DF Approach, Climate based Daylight Simulation, Post occupancy Study, Simulation model callibration

INTRODUCTION

It is well established that people value daylight in their work environment (Boyce etal.,2003). Daylight in buildings provide many benefits to building occupants. These benefits include the displacement of artificial lighting and reduction in sensible load with corresponding reduction in energy consumption. There are also numerous intangible benefits like Improved occupant satisfaction and comfort, increase in productivity ((Abdou, 1997; Heschong Mahone group, 2003), higher attention spans, etc.

The client here had a singular focus to improve 'usable' daylight access to all occupants within the large open plan offices. This not only meant meeting min. illuminance levels in at least 80% of open offices but also to provide glare free usable daylight by means of only static shading device and complete avoidance of internal blinds. This laid a path to some specific design targets which were adhered to in detail during the design stage.

Daylight prediction models and computer software have rarely been validated against real time case studies with real occupancy. The degree of accuracy, behaviour profile of various geometries and their surface properties using computer simulation are also not very well known. The Primary Intent of the authors was to validate the ideal metric to bridge the gap between simulated and measured results. The secondary intent was to identify all parameters relevant to built geometry, material parameters and simulation parameters that influence the degree of accuracy in prediction of daylight within the space.

INTRODUCTION TO CASESTUDY

Buildings referred in this study are SDB (Software Development Block)-1, SDB-2&3, SDB-4&5 in Infosys Pocharam Campus of Hyderabad. Figure 1 showcases SDB-1 as Phase 1, SDB-2&3 as Phase 2 and SDB-4&5 as Phase 3. The authors were involved in the project post the completion of SDB1 and undertook several simulation studies to evaluate Daylight performance, Thermal Comfort and Energy consumption. This particular paper highlights only the daylight aspect of the study covering in detail simulation work & onsite measurements undertaken to validate the results at each phase, the key findings which formulated future guidelines for all simulated work.

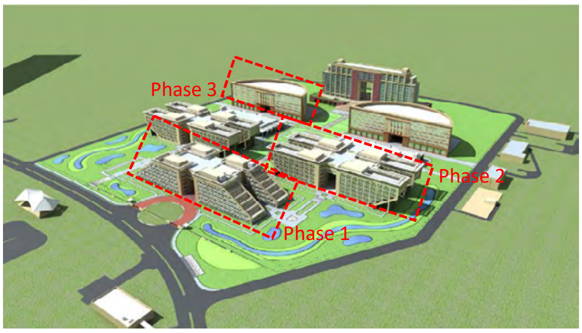

Figure 1: various phases of project covered in this study

METHODOLOGY

Overall study has been undertaken in 3 phases. Phase 1 in 2010, phase 2 in 2012 and phase 3 in 2014. Boundary conditions of the onsite measurement-based calibration study was formulated based on the research work of Reinhart CF, Walkenhorst O,2001. and Mardaljevic.J, 1995. The various measures have been detailed further.

Phase 1 study was undertaken post construction of SDB-1. It was undertaken as a calibration study to optimize simulation parameters and cross-validate the Daylight Factor approach. This was undertaken in order to improve the accuracy of prediction at the design stage in subsequent buldings.

Phase 2 study was undertaken post the construction of SDB 2 & 3 (identical buildings). These two buildings were designed and optimized based on DF approach. In this phase, in addition to onsite measurements, a post occupancy survey was conducted to understand the user response to illuminance levels and their perception of overall visual comfort.

Phase 3 study was undertaken post the construction of SDB 4&5. These two buildings were designed and optimized based on CBDM approach and metrics such as UDI and DA were used to rationalize various design decisions. Onsite measurements were taken to validate the various key design decisions undertaken.

SIMULATIONS & MEASUREMENT:

Across all three phases, simulations were undertaken in Ecotect. In phases 1 & 2, the simulations were undertaken using Radiance, a lighting simulation program that was initially developed by Greg Ward in the late eighties at Lawrence Berkeley National Laboratory (Ward and Rubinstein, 1988). which has been validated as early as 1995 by Prof. Mardaljevic, J and later in 2006 by means of a survey based study (Reinhart and Fitz, 2006).

In Phase 3, simulations were undertaken using DAYSIM: One of the most widely used back-end tool to perform CBDM. It implements a modified version of *rtrace* for the light redistribution simulation. The publicly available version use the Tregenza patches scheme for skylight and up to 65 points over the sun path as sunlight sources, with the sun luminance interpolated between the closest four points to the actual sun position. The luminance distribution is derived from weather files data using the Perez All-Weather model.

All material reflectance of opaque materials was identified using reflectance sample card of CIBSE's lighting guide 11 and all glazing data was based on manufacturer spec sheet.

Opaque Element	Material	Reflectance
CEILING	White painted ceiling	0.8
FLOOR	Concrete floor with tile	0.3
WALLS	Light coloured wall	0.5
LIGHTSHELVES	White painted timber/ aluminium	0.8
GLAZING MULLION	White painted Aluminium	0.6
VERTICAL FINS	Frosted glass	0.15

Transparent Element	Transmittance
DOUBLE GLAZING - daylight pane	0.62
DOUBLE GLAZING -Viewpane	0.41
FROSTED GLASS IN VERTICAL FINS	0.15

Table 1: Typical Material reflactances used in the study at the beginning of study

The opaque reflectances varied slightly across the study and glazing elements changed based on the actual spec recommended, which was based on thermal analysis, orientation, final proposed shading and daylight distribution studies.

METRICS

Following are the three metrics elaborated in the study and their definitions are cited from Reinhart C F, 2010.

Daylight Factor (DF):

The *daylight factor* is defined as the ratio of the indoor illuminance at a point of interest to the outdoor horizontal illuminance under the overcast CIE sky.

Daylight Autonomy (DA):

The *daylight autonomy* at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone. In contrast to the more commonly used daylight factor, the daylight autonomy considers all sky conditions throughout the year.

The minimum illuminance level corresponds to the minimum physical lighting requirement which has to be maintained at all time.

Useful Daylight Illuminances UDI):

Useful Daylight Illuminances (UDI), proposed by Mardaljevic and Nabil in 2005, is a dynamic daylight performance measure that is also based on work plane illuminances. As its name suggests, it aims to determine when daylight levels are 'useful' for the occupant, i.e. neither too dark (<100 lux) nor too bright (>2000 lux).

Based on the upper and lower thresholds of 2000 lux and 100 lux, UDI results in three metrics, i.e. the percentages of the occupied times of the year when the UDI was achieved (100-2000lux), fell-short (<100 lux), or was exceeded (> 2000 lux)

ONSITE MEASUREMENT:

Simultaneous illuminance measurements were taken for all internal test points and outdoor lux level using calibrated lux level meters for equivalencies. Two identical lux meters of Extech make were used in the field studies. Outdoor measurements were taken in a clear area free from obstructions to measure precise outdoor sky illuminance. Indoor measurements were taken at desk level at 750mm from FFL. On each day 3 sets of measurements corresponding to morning, noon and evening were taken. Each test point corresponded to the position of an occupant in the space

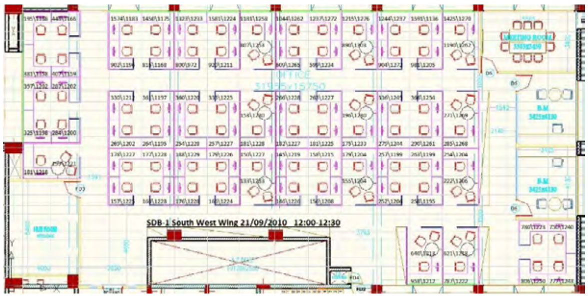

Figure 2: SDB1's sample floor plate with marked data of measurements

PHASE 1 STUDIES:

In Phase 1, illuminance measurements as described above we were taken twice in the year. The first set was taken around Autumn equinox, from Sept 20th to 24th and the second set was taken in winter from Dec 20th to Dec 24th. All openings on the East and West facades were blacked out so as to measure the impact of the primary North-South facing opening only. All measures were taken on level 3 of the G+5 floor building to negate any impact of ground and foliage. Additionally, the span of 5 days was used to measure following conditions:

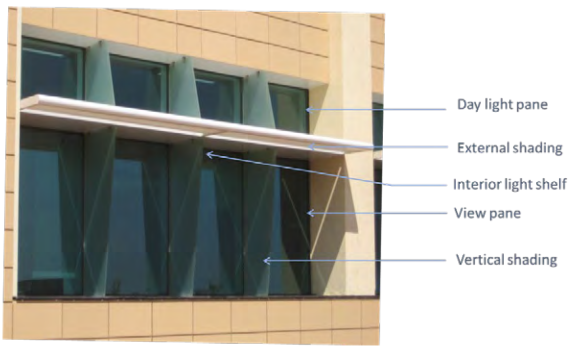

Figure 3: Typical south facade for SDB1

Day 1	Only daylight panes on the external facades were left open. All view panes and Courtyard side glazing was blacked out	To assess the impact of Day pane and the internal lightshelf only from the unobstructed external facades.
Day 2	Only daylight panes on both the external façade & Courtyard facade were kept open. All view panes were blacked out.	To assess the impact of Day pane and internal lightshelves only from both sides of the floor plate (external and courtyard façade) with building obstruction on the courtyard side
Day 3	Only View panes on the external façade was kept open. Rest of the glazing (all day panes on both facades and view panes on courtyard side) were blacked out	To assess the impact of View pane from the unobstructed external façade only
Day 4	Only View panes on both external as well as courtyard facades were kept open. All the daypanes were blacked out	To assess the impact of View pane only from both sides of the floor plate (external and courtyard façade) with building obstruction on the courtyard side
Day 5	All panes are open (external façade & Courtyard side)	General open condition which will be observed across year.

Table 2: tested Conditions across 5 days in phase 1 studies

Key objective of doing the above said conditions was to understand the impact of window configurations and their individual contribution to illuminance levels within a space. Only Day 5's results are discussed in this paper.

PHASE 2 STUDIES:

Field measurement were done on June 20th, 21st and 22nd of 2012. Additionally, visual comfort survey was conducted for the occupants of SDB-2 to correlate the measured lighting levels against user perception of visual comfort.
On day 2 measurements were impacted due to rains and as such only data from day 1&3 are used in this study.

Measurements were again taken on level 3 of the building. Floor layout and building size is identical to SDB1, however the window configuration and size of shading is slightly different.

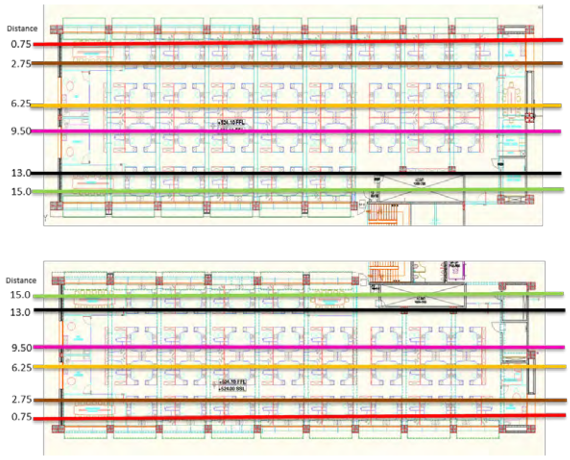

Figure 4: SDB 2's typical floor plate indicating the colour coding for visual comfort survey

A survey sheet was distributed amongst the daily users of the building. To maintain anonymity, these were not marked to position, but generalised into groups based on Orientation, Location and distance with respect to windows. This was achieved by colour coding the sheets and distributing them as shown in the image above. A total of 320 users participated in the survey.

PHASE 3 STUDIES:

In this phase, field measurements were taken only on 22nd June 2014. Measurements were again taken on level 3 of the building. Floor layout and building size is different to both phase 1 & phase 2. South façade scheme is identical to earlier buildings, , however the window configuration and size of shading is different. North façade is drastically different in this phase.

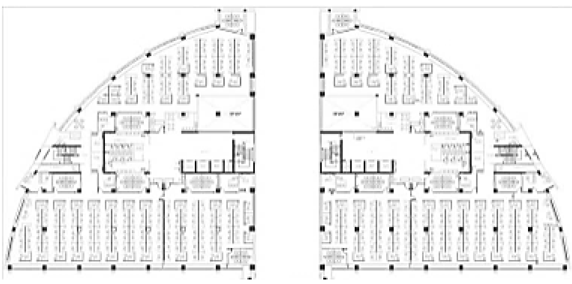

Figure 5: SDB 4&5's typical layout

LIMITATIONS:

Authors were involved in the project post construction of SDB1. Hence, phase 1 studies were conducted to set up a baseline for all future studies and aid in the design process of SDB 2&3. As such no visual comfort study was conducted and only calibration studies were undertaken.

DISCUSSION & FINDING

PHASE1:

In 2011, design guidelines worldwide recommended Daylight factor as the metric to measure daylight level. Daylight factor (DF) is a simple ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky. The limitations of this metric are well documented as highlighted by Mardaljevic, et.al,2009. DF is insensitive to both building orientation (due to symmetry of the sky) and the location (as it is a ratio). The climate of the location (sunny or cloudy sky) is also not considered.

Given that project location is Hyderabad, a location with "clear sky with sun" as sky condition for larger duration of the year, validity of DF as metric was challenged given the above said limitations. Hence, the caliberation for

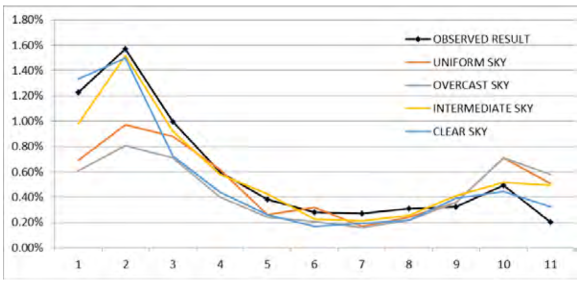

Figure 6: Day 5's DF distribution graph- Before Calibration

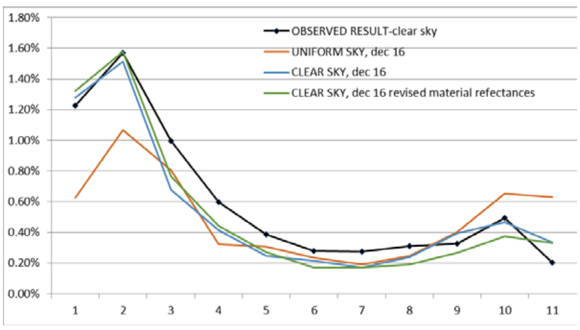

Figure 7:Day 5's DF distribution graph- After Calibration

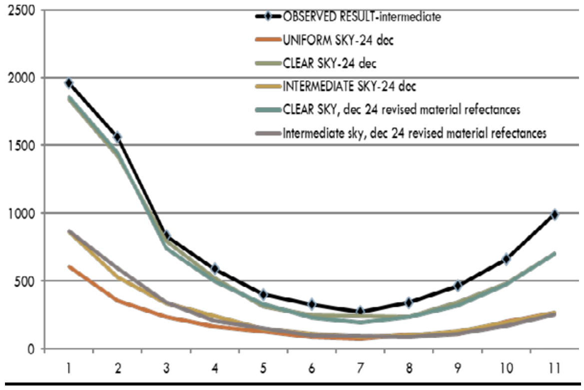

Figure 8: Day 5's Lux level Distributuion graph after calibration

In the Daylight factors distribution graph it was noticed that for the measured outdoor sky illuminance, all sky distribution models followed the same trend line as the measured data, however they were varying closer to the façade. Overcast sky condition was consistently underpredicting, whereas clear sky condition was closest to trend line. As step 1 only reflectances of materials were corrected based on CIBSE's reflectance sample card and simulations re-run. It was observed that it improved the simulation output as seen in figure 8, where the difference in measured data and actual lux level have been brought down to an average of 11%, however the DF graph didn't reflect the same with Clear sky condition given the limitations. The key inferences at this stage were as follows:

- Run clear sky Lux level simulations to predict absolute values on any given day, preferably March 19th, June 7th and Dec 16th (based on the weather file of Hyderabad and perez's all weather sky model, these days were closer to the sky illuminace measure in the field study)
- Run overcast sky based simulations for parametric studies and to make all design decisions and cross verified by lux level runs.

PHASE 2 – CALIBERATION STUDY:

The building section facing north as the primary façade had a marginal error in prediction given that north façade didn't have a heavy shading design, with 400mm vertical fins every 1260mm and only the wall depth providing the required horizontal shading. The only error was the change in construction detailing on site compared to the design case (figure 9).

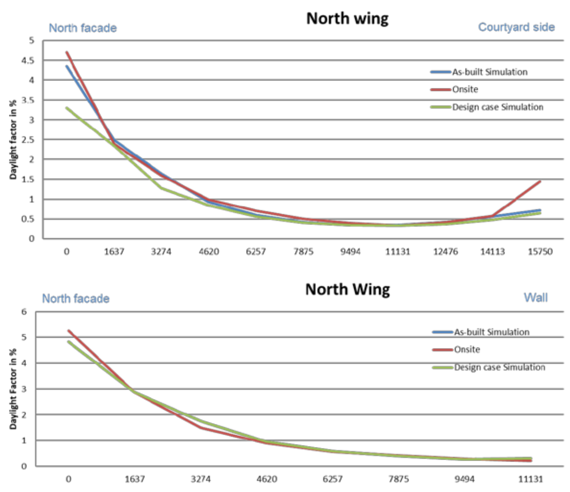

Figure 9: North Wing's data as on 20th June

However south façade required a detailed calibration study as shown in figure 10.

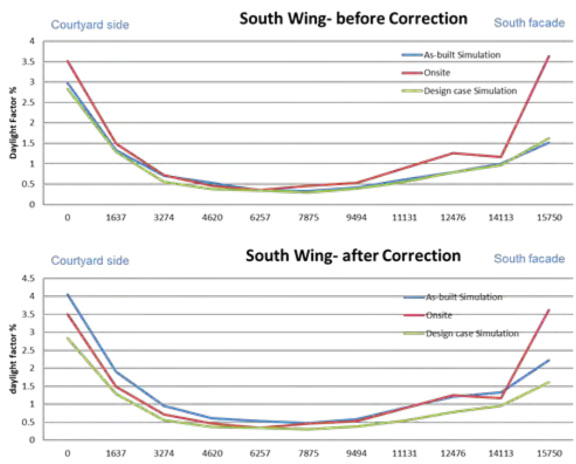

Figure 10: South wings data on 20th June

Key findings of phase 2 calibration studies were as outlined below:

- For the as built simulation the reflectance of the light shelf has been reduced to 0.6 from 0.8, which was used in design case simulation. This is to account for the dust that is accumulated on the lightshelf over a period of time.

- Other reflectances are as identified in the previous study from SDB 1.

- The most important inference from this exercise are the revised simulation parameters.

- In the simulation exercise it was noted that simulation model predicted on par with the actual observed daylight distribution, however on south side it under predicted.

- This was because of the difference in geometry on north and south side.

- On north side there are only fins, but no external lightshelf. In simulation this configuration is defined as a simple geometry.

- On the south, with the presence of the external lightshelf with louvers, the geometry should be considered as a complex geometry and sampling parameters like *ambient division*[1] and *ambient super sampling*[2] and *ambient accuracy*[3] had to be increased.

[1] setting the number of ambient divisions to n. The error in the monte carlo calculation of indirect illuminance will be inversely proportional to the square root of this number. A value of zero implies no indirect calculation.

[2] setting the number of ambient super-samples to n. Super-samples are applied only to the ambient divisions which show a significant change.

[3] setting the ambient accuracy to acc. This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

PHASE 2 – VISUAL COMFORT SURVEY:

Overall findings from the visual comfort survey were as follows

- People sitting in well daylit spaces spent more time at desk compared to people sittng away from natural light. The increase in time spent at the desk was a average of 45 min per day.

- Occupants preference of daylight vs artificial light was highly varied. However, 95% of the occupants preferred having daylight only or a combination of daylight and artificial light.

- Less than 5% of the occupants preferred artificial light over daylight or greater artificial light with daylight.

- Even with no direct sun on the screen or workstations, occupants perceived some glare in various parts of the room. Through onsite observations, it was noticed that this

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was largely visual discomfort due to higher contrast ratios in the line of sight, between the screen and the wall behind.

- Many complaints were from Level 2. This was caused by external elements, and in this case, the roof of the food court which had a high reflectivity roof paint on it.

- It was also noticed that for persons sitting right next to the façade, the contrast ratio between screen and wall behind was high, especially when they did not sit perpendicular ot the façade. This was also reflected in the survey.

- Most of the occupants seem to be in favour of blinds and glare restrictors. When further questions were asked, this requirement stemmed from the perception that *"blinds are a privilege"*

Figure 11: figure showing the time spent by occupants in office space

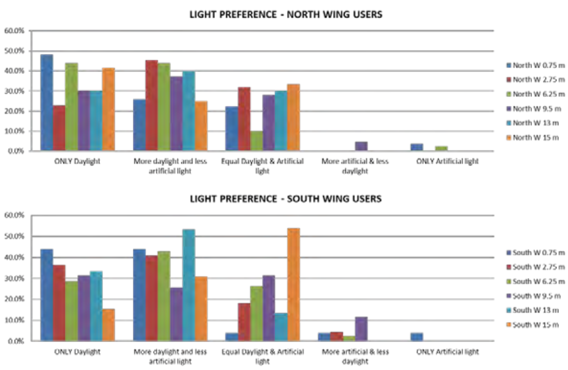

Figure 12: Light preference of User in both wings

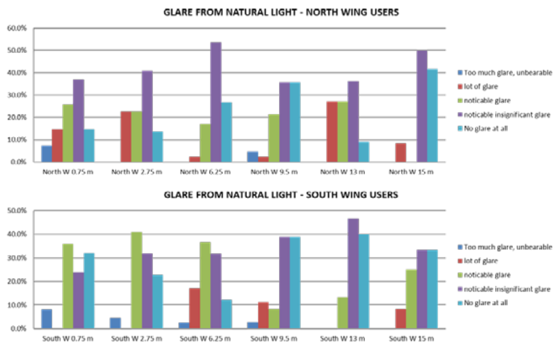

Figure 13: percieved glare of the occupants

Based on these surveys new guidelines were laid out for all future buildings. These were as follows

1. An aisle space of a minimum of 1m from the inner façade line of an external façade with fenetrations has to be introduced in all areas to ensure minimisation of perceived glare

2. Workstations have to be designed in such as way that users would always sit perpendicular to the windows

3. Integration of blinds within the work station partitions was considered

4. Task lighting was provided at every workstation.

5. This study also ensured that all future designs had to include glare studies during design stage.

PHASE 3:

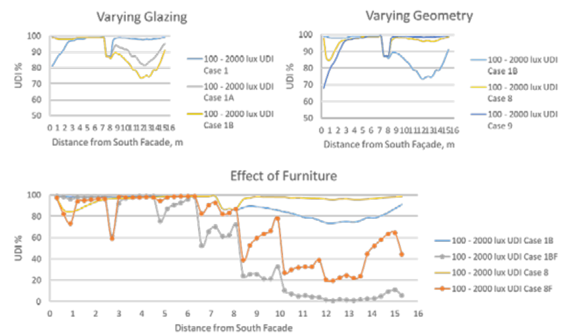

Figure 14: parameters studied during phase 3

In phase 3 impact of varying glazing and geometry specs and furniture was studies using CBDM and it was inferred that level of detail in model and furniture played a significant role in prediction. Traditional compliance approaches don't ask for built furniture in simulation

CONCLUSION

General trend in all three phases was that design case simulations were under-predicting compared to the measured cased. In the phase 1 studies, mean std deviation was around -18% which reduced to -11% in phase 2 studies and in phase 3 studies it was around 7%. This was achievable in this project as the material palette in terms of reflectance was standardized and detail of modelling and simulation parameters were optimized based on learnings. Other key insights from the occupant perspective paved way for us to focus more on visual comfort while achieving the high-performance targets. Key learnings of this study became the part of design guidelines for all future buildings. They are surmised below

- To achieve a well daylit space with good uniformity across all occupant areas, a min 1m to max 1.5-meter aisle space must be left next to the external façade
- As far as feasible, furniture should be designed so that occupants sit perpendicular to the façade to minimize any glare
- Workstations have to be carefully designed and a certain amount of control has to be given to the occupant over her/his immediate surroundings.
- Even though external shading system is simple combination of horizontal and vertical elements, It must be simulated as a Complex Fenestration System.
- The furniture should be included in the model during parametric simulations.

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JOULE RECIPES: A NOVEL CONCEPT TO ELIMINATE ENERGY WASTE IN BUILDINGS

Ananthapadmanabhan G S [1], Listin Abey Mathew [2]

[1]*Analytics and Automation*
Smart Joules Pvt. Ltd
New Delhi, India
ananthapadmanabhan@smartjoules.in

[2]*Analytics and Automation*
Smart Joules Pvt. Ltd
New Delhi, India
listin@smartjoules.in

ABSTRACT

Joule Recipes promises to eliminate energy waste at a scale comparable to the LED revolution, by uncovering and continuously correcting hidden inefficiencies in operations of dynamic energy systems such as central air conditioning.

Joule Recipes are energy-saving algorithms that crawl data collected from sensors and equipment, looking for trade-offs and optimizations. They then either send alerts to specific individuals nudging them to take specified corrective actions or automatically tune operational parameters of end-use equipment. For instance, Joule Recipes may observe suboptimal condenser circuit operations and increase the frequency of cooling tower fans while turning two condenser pumps down, minimizing overall energy.

What makes Joule Recipes different is their simplicity and flexibility. They can be designed and deployed by anyone who can operate a smartphone, completely eliminating the need for speciality engineers to code individual controllers every time a facility engineer wishes to test an optimization logic. Furthermore, Joule Recipes can operate on both real-time and time-series data from one or more sensors without regard to their physical location, and even on values computed from a number of sources. By lifting all restrictions on the types of input data, computations, and controls and by making their design and deployment accessible to all, Joule Recipes make operational energy savings substantial and scalable.

This paper presents several real-life examples of how Joule Recipes have been used to save energy in Hospitals by modulating set points of cooling towers, chillers, pumps and AHUs.

Keywords—Building energy performance, Maintenance, BMS, Energy optimization

INTRODUCTION

The future of energy management is digital. With this realization, Smart Joules an energy saving company (ESCO) whose mission is to eliminate energy waste through innovations in continuous energy optimization has designed a proprietary Building Management System called DeJoule, which consists of high-performance IoT devices and software for effective and instant computation and user-friendly interaction. DeJoule collects and analyses energy and system performance data, and enables automatic controls of heavy energy-consuming assets. It collects data every single minute, which enables high-resolution analysis based on which optimum control sequences can be discovered and acted upon. This paper discusses one of the most innovative and critical features of the DeJoule – Joule Recipes.

NEED FOR JOULE RECIPES

Reducing wastage in an energy system requires efficient system designs and optimum operational practices. A research programme initiated by International Energy Agency concluded that 20%-30% of energy savings are achievable by recommissioning of HVAC systems to rectify faulty operation (IEA EBC Annex 34, 2006). The findings suggest the requirement of a computer-based data collecting and monitoring system which can also perform Fault Detection and Diagnosis (FDD) techniques. The concept of Joule Recipes arises from the requirement of taking continuous optimal control actions & FDD techniques in a HVAC system. Joule Recipes solve the seemingly impossible manual task of continuous data collection, monitoring, analysis and control action by integrating this process with the BMS (DeJoule).

Consider the case of a HVAC plant that contains chillers and several numbers of pumps, AHUs and valves. The energy optimization opportunity in this system is tremendous by controlling the ON/OFF or modulating the VFD frequency and temperature setpoint. The manual labour that is required in controlling all these parameters throughout a day is impractical even after considering the energy savings. But a semi-autonomous control (Joule Recipes) can easily achieve the prospect.

Joule Recipes were first developed in the context of controlling HVAC systems in a building. But the flexible architecture allows extending the Joule Recipe capabilities to other energy systems such as low-pressure steam, hot water and compressed air.

JOULE RECIPES

Joule Recipes are energy-saving algorithms that work on the IFTTT (If This Then That) logic. A recipe can perform algebraically (+, -, >, <) and logical (OR, AND) operations on almost all the configured data points in the DeJoule. These data points are termed as "observables" in Joule Recipe. If the logical operation gives a true condition (IF THIS) then the recipe can execute a set of alerts or/and a set of control actions through DeJoule.

Controllable Parameters Through Joule Recipes

Before getting into the mechanics of how energy-saving Joule Recipes are created and deployed, it's important to understand the parameters that can be controlled to achieve operational optimization of central air conditioning (HVAC) systems, the first dynamic energy system that DeJoule is configured to optimize:

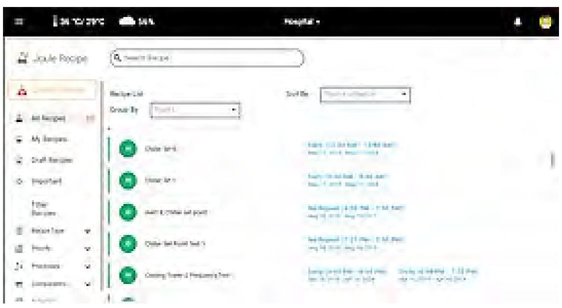

Figure 1: Joule Recipe Page in DeJoule

On/Off Control of Chillers, Chilled Water Pumps, Condenser Water Pumps, Cooling Towers and Air Handling Units (AHUs).

Temperature Setpoint Control of chilled water leaving from the Chillers to the building or of area temperatures cooled/heated by AHUs.

Speed Control through VFDs of Chilled Water Pumps, Condenser Water Pumps, Cooling Towers and AHUs.

Percentage Opening of Motorized Two-Way Valves through Actuators to regulate the flow of chilled water through AHUs.

Joule Recipe Example

Suppose there is an AHU at site A, which operates for 11 hours a day between 09:30 AM and 08:30 PM to deliver cooling to the Library area. Without precise operations, energy waste would likely be associated with the AHU's operations due to one of the following reasons:

- Excessive operational hours: The AHU would likely start before 09:30 AM or stop after 08:30 PM since its difficult for operations staff to always be precise.

- Overcooling / Overheating: Suppose the actual temperature requirement of the cooled area is 24℃ but the area is cooled to 22℃.

In this context, Joule Recipes can lead to operational optimization in the following ways:

a) A Joule Recipe can notify concerned individuals via Joule Track's User Interface, SMS or email when an AHU starts before scheduled start time or fails to stop by the scheduled stop time.

b) A Joule Recipe can generate a control command for DeJoule's IoT devices to start and stop the AHU at scheduled times.

c) A Joule Recipe can monitor the area temperature and reduce the frequency of the blower or reduce the percentage opening of the two-way valve so that the area is not overly or unnecessarily cooled.

d) Joule Recipes can automatically report Figabnormalities in AHU operations such as untimely stops, non-modulating valves, open valves during

AHU-off times, bypassed VFDs and improper VFD frequencies, and notify the same to concerned facility staff.

JOULE RECIPE MECHANICS

Joule Recipe is a powerful tool offered by DeJoule. This can be understood by its creation, capabilities and novelty.

JOULE RECIPES: CREATION

One of the important features of Joule Recipe is the simplicity in its creation. The steps involved in this process is simple and intuitive and these steps can be divided into four: (i). Describe, (ii). Logic (Observables), (iii). Actionable, (iv). Schedule.

Describe:

A user can write hundreds of recipes for any given site. These recipes can be based on any one of the HVAC assets or some operating condition. The describe part of the recipe make it easier for the user to organise the recipe according to name, asset, function and priority.

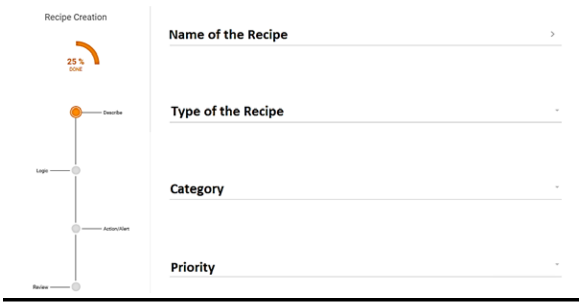

Figure 2: Recipe Description

Logic:

Observables: In this section of the recipe, the user creates a logical expression using some HVAC asset parameters and mathematical operators. The observable section has two parts: Parameter selection and workspace.

Figure 3: Recipe logic (observables)

Parameter Selection: All the data points that are configured to DeJoule are available for the user to select. This includes HVAC asset parameters, area temperatures and energy meter data.

Workspace: in this session, there is a recipe editor, a set of algebraic operators (+, -, >, == etc), logical operators (AND, OR), some special functions (Persistence, Maximum, Minimum, etc.) and time interval of observation. The logical expression is written in the recipe editor using all the operators. Based on time interval value, recipes can be classified into two: Normal (instantaneous) recipe, Time-series recipe.

Actionable:

In the actionable section, there are two options for the user: Alerts and Action. User can create recipes that contain single or multiple alerts and single or multiple actions. A recipe will execute the alert or action only when the logical expression on observable section is satisfied.

Alert: Alert box can select any number of DeJoule registered users to get an alert when the recipe observable is satisfied. The description of the alert and suggestion to improve the condition can also be included in the alert.

Action: In the action box any DeJoule controllable asset can be selected and a single action can be selected from the options such as ON/ OFF, Chilled Water Temperature Setpoint, Frequency of motors & pumps, Actuator Valve position based on the asset. There is also an option to give notification to users regarding the action and to assign a user responsible for the recipe.

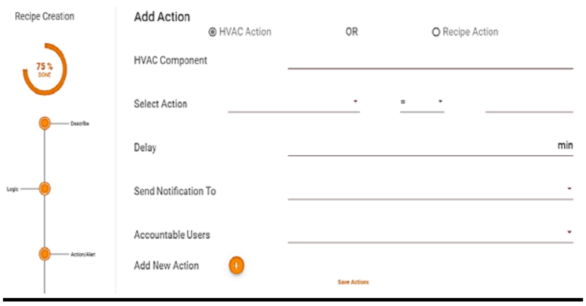

Figure 4: Recipe Actionable – Action Section

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Schedule

After creating observable and actionable for a recipe and saving it, the user can decide on a schedule for the recipe to run. The schedule gives the recipe extra flexibility and eases the load on the IoT device. The schedule can decide the dates and times at which the particular recipe runs and a recipe can have multiple schedules also.

JOULE RECIPE CAPABILITIES

Joule recipes are based on a relatively simple If This Then That (IFTTT) logic with a schedule. This logic also explains the steps involved in recipe creation i.e., Observables (If This), Actionable (Then That) and Schedule. Each of these steps having different levels of capabilities all of which working together makes the recipe a powerful tool.

Observables: In observables section, a user can select any number of data points that are configured to DeJoule and perform various operations on them to create a true or false statement (comparison).

E.g. Average Apparent Power (360TR Chiller)> 10. Here the inequality operator used gives either a true or false condition.

In recipes, as of now, there are five inequality operators to create these comparisons – greater than, less than, greater than or equal to, less than or equal to and equal to. These comparison statements can be extended using logical operators (AND, OR). Comparison statements can also be constructed using arithmetic operators such as +, -, ×, /. This enables recipes to create newly calculated parameters and create comparison statements with them.

E.g. 1. (Average Apparent Power (Chilled Water Pump) >1 AND Output Frequency (Chilled Water Pump) <45)

2. ((Average Apparent Power (Chilled Water Pump 1) + Average Apparent Power (Chilled Water Pump 2)) >10)

Observation Time: All the recipe logics that have been discussed so far can be classified into instantaneous recipes because in all such recipes only one data point (taken in a one-minute time interval) is taken into account. There is another category of recipes that takes decision based on a set of data points (taken in an observation interval of several minutes or hours) that are called time series recipes.

DeJoule collects data every one minute. If the user sets the observation time to say 10 minutes, the recipe will collect the previous 10 data points from the scheduled time. There are several time series functions that utilize this feature to create comparison statements. They are persistence function, average function, maximum function and minimum function.

Persistence Function: This function will check a particular asset parameter to the user-defined condition and count the number of true conditions across the user-defined time interval. If the count of true conditions is greater than or equal to the persistence percentage given, it will execute the alert or action linked with the recipe.

Average Function: This function will check the average value of a particular asset parameter across the user-defined time interval. The function returns a single value which can be used with any arithmetic operators.

Maximum and Minimum Function: This function will check the maximum value (or minimum value) of a particular asset across the user-defined time interval. The function returns a single value which can be used with any arithmetic operators.

Reproducibility: Joule Recipes are flexible across sites. A set of recipes that are created for a site can be copied and applied to another site with ease. This makes the process of bringing hundreds of similar sites under recipes an easy task.

JOULE RECIPE NOVELTY

Joule recipes are different from the normal automation tools and can change the entire landscape of plant room control. The major differences are listed below:

Time Component: A good plant room always depends on the effectiveness of its operator in taking the best decisions based on the real-time conditions. Joule Recipes extend this knowledge of an operator's decision-making abilities and add a flexible time component to it. A Joule Recipe can operate 24 hours, 365 days with the deployed logic of the operator and makes continuous energy optimization a reality.

Ease in creation: Joule Recipes follow an intuitive schematic in its creation as illustrated in the previous section. A normal operator without having prior knowledge in any computer language can create recipe through a simple user interface offered in the DeJoule web platform. While other automation schemes follow some proprietary schematics and not accessible to normal plant operator due to its complexity.

Simplicity in deployment: Comparing to other automation schemes that are hardcoded into a controller, Joule Recipes are created in a web-based platform and send to IoT devices through the internet. This gives the flexibility of deploying automation schemes to distant plant rooms from anywhere and anytime. Any change in the present conditions can also be easily deployed through the internet. While other schemes require frequent revisits to the site to configure the required changes.

Transfer of knowledge: A well-performing plant room owes to the experience level of its operator and his/her decision-making capabilities. It also means this performance is most of the times limited to some sites only. But a well-performing Joule Recipe site (utilizing knowledge from an experienced operator), can extend this performance to all other sites by copying the recipes. This will result in a huge number of optimized sites across the nation.

Self-Diagnostics: The DeJoule platform can rank its Joule Recipes based on the amount of savings it brought on the site. This will help other operators to select the most effective recipes for their sites. This self-diagnostic nature of Joule Recipes is one of the unique features of the scheme. Joule Recipes can also take the loss of data as an observable parameter and generate alerts during data loss.

Joule Recipes Vs All Variable System

In all variable systems every HVAC asset operate on a variable configuration and gets optimised automatically based on feedbacks such as DPT pressure (for chilled water circuit) and condenser entry temperature (for condenser water circuit). These systems are very robust and don't require any operator interference.

Joule Recipes claims superiority over these systems due to the fact that it can implement any mathematical model the recipe writer adopts to ensure energy savings. The response time of recipes are very small compared to All Variable Systems and exercise a broader control range on assets. Recipes can deploy control over individual assets based on any number of HVAC parameters. For example – setpoint management schedule of chiller can be deployed based on outside air temperatures with recipes and at the same time, setpoints can be revised based on observing area temperature trends of critical areas.

RECIPES AND THEIR IMPACT: CASE STUDIES

Case Study 1

Alert Recipe – Less Flow in Condenser Line

A condenser water line is an open loop at cooling tower. For the effective heat rejection at cooling towers, a part of the condenser line water will get evaporated. Therefore, makeup water is provided at cooling towers to compensate for the water loss. However, if the amount of makeup water is not sufficient and then air gets trapped inside the condenser line. These air pockets reduce the heat transfer from the refrigerant at the condenser and reduce the chiller efficiency. The prolonged condition can also lead to permanent damage to the pump impellers.

Presence of air pocket in the condenser line (due to less water) can be identified from condenser line water flow data. Hence an alert recipe that observes the condenser line water flow can warn the site managers about the incident within minutes. The recipe can also suggest the remedial measure that is to start the makeup water pump.

Figure 5 shows a less flow in the condenser line situation at site B. The presence of air pocket inside the pipes makes the water flow very irregular. Here the flow can be seen to be oscillating between 400 GPM and 325 GPM. These huge oscillations can create cavitation, seal failure inside the condenser water pump and permanently damage the pump impellers.

A fail-safe recipe is deployed to generate alerts based on the condenser line flow. So, at any point of the day, if this condition occurs, an alert is generated to the site manager (operator) and necessary action can be taken (Figure 6). The feature is a classic case of alert recipes helping the HVAC plant operation.

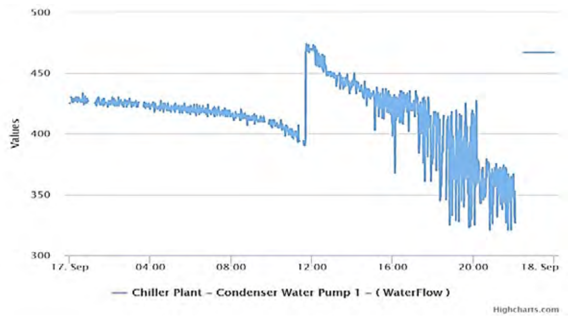

Figure 5: Less flow in condenser line persisting for more than 6 hours (No recipes deployed)

The alert recipe checks for the instantaneous condition when the pump flow reduces below 350 GPM when the pump is running. If the condition is satisfied, an alert "Less flow in condenser line" is sent to the concerned personnel. In this case, if the makeup pump is also configured to DeJoule, the recipe can start that pump without the intervention of operators using 'actionable'

Figure 6: Alert created by Joule Recipe about less flow in the condenser line (preventive maintenance)

Case Study 2

Action Recipe: Setpoint Schedule of Chiller.

Cooling demand in commercial buildings like hospitals varies throughout a day, but the chiller setpoint value is kept constant throughout the day. This offers an energy optimization opportunity for the facility (Rahman, S. *et al,* 2011).

Reducing chiller setpoint by 1˚F can bring about 2-3% of saving in overall chiller consumption. Most of these set point altering can be done during the night/ off-peak while the cooling load is less. Several Joule Recipes can be effectively deployed to ensure a 24-hour schedule of chiller set point.

Figure 7 shows the chiller setpoint value before Joule Recipe based optimization, stays the same throughout the day/week even during off-peak time. After deploying a schedule for the setpoint changing seven times a day (figure 8) according to the load demand, quality of service along with energy savings are ensured.

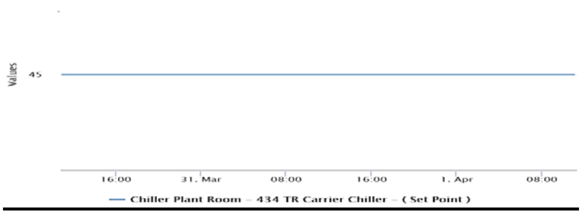

Figure 7: Chiller set point before Joule Recipe based setpoint management

The drop-in chiller energy consumption is illustrated in two-year data (figure 9). The year 2018 is showing a clear drop in consumption compared to 2017 due to chiller setpoint management. The average outside air temperature during the sample period only differs by 1ºC.

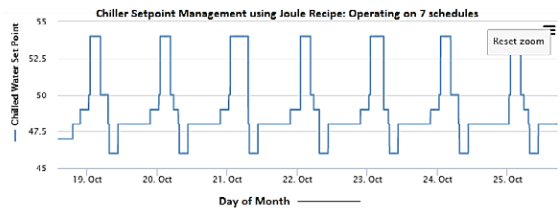

Figure 8: Chiller set point after setpoint management

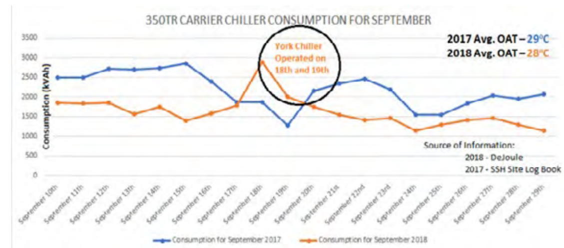

Figure 9: Energy consumption reduction in chiller due to setpoint schedule

Setpoint scheduling brought about daily savings of 190-200 kWh for a day in this particular case for a chiller of 350 TR capacity. Extrapolating this value to one-year accounts to more than 70,000 kWh. This is a significant amount of savings which can contribute to both the building energy efficiency and its carbon footprint reduction.

Case Study 3:

Action Recipe: Chilled Water Circuit Optimization.

Chilled water from the chiller is circulated throughout the building's AHUs using chilled water pumps. A minimum flow has to be maintained in the chilled water line at a level equivalent to 2GPM per ton of cooling and pressure at the farthest AHU should be at least 0.8 – 1 Kg/cm^2(Bela G. Liptäk., 1995).

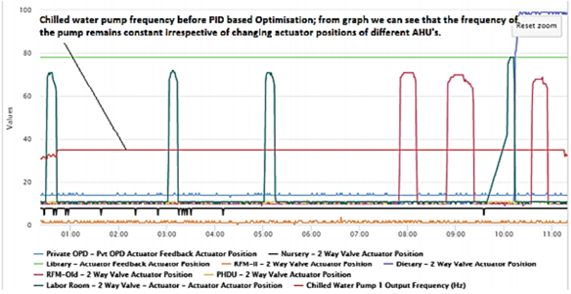

Figure 10: AHU actuator valve position and chilled water pump frequency (before optimization)

In hospitals, not all the AHUs run 24 hours. Some AHUs are turned off after their scheduled run hours. Even though AHUs are off, if the valve in the chilled water line is open, there is no effect on the chilled water line. Now when AHUs are off and AHU valves are closed, the flow in the chilled water line can be reduced by reducing pump VFD frequency, resulting in savings in pumping costs (Bela G. Lipták, 1995). In this example, Joule Recipes are deployed to monitor actuator valve positions throughout the building and to modulate chilled water pump frequency as per the number of valves closed. Figure 10 shows an unmodulated chilled water pump frequency even when several AHU valves are closed. This normal operating condition is modified using Joule Recipes to achieve a modulated chilled water pump. Figure 11 illustrates this frequency change with respect to the closed AHU valves.

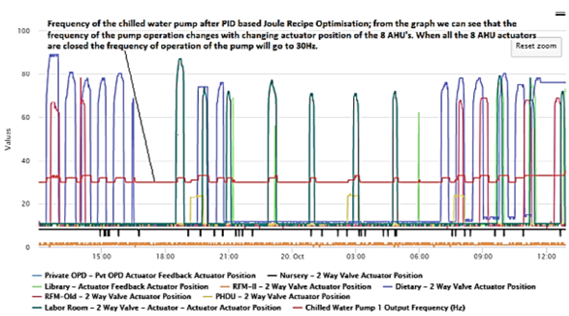

Figure 11: AHU actuator valve position and chilled water pump frequency (after optimization)

This resulted in a reduction in chilled water pump energy consumption. Daily savings from this optimisation were 140 – 150 kWh per day (figure 12) in this particular application for an 11kW pump.

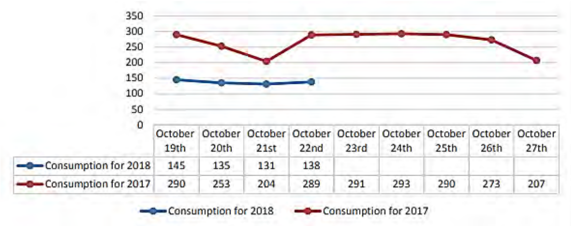

Figure 12: Reduction in chilled water pump consumption

Case Study 4:

Action Recipe: AHU Run hour implementation

Buildings like hospitals have several AHUs working in different schedules. Most of AHUs have a well-defined schedule, but the operator may forget to turn off the AHUs as per the run hours. DeJoule data enables the user to find these extra running AHUs and turn it off using Joule Recipes.

Figure 13 shows the deviation of actual run hours of dietary AHU from the scheduled run hours. Most of the days AHU run hours exceed the 7 hours run time to 16 hours run time. These extra run hours can be easily regulated using Joule Recipes and the schedule can be enforced to reduce the huge energy loss. After deploying these recipes, the actual run hours of the dietary AHU are shown in Figure 14.

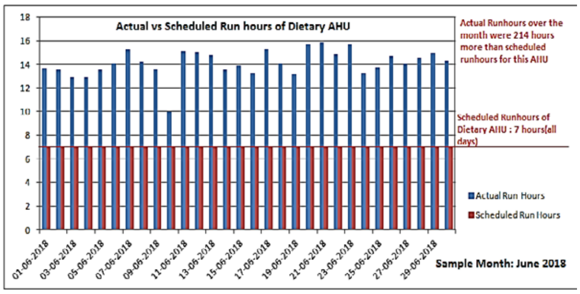

Figure 13: Actual vs Scheduled run hours of Dietary AHU of a hospital

Extra run hours of AHU account energy loss from the AHU and the cooling load on the chiller and chilled water pump. In the case of dietary AHU, the cooling load is 20TR. The total energy savings from both AHU and chiller add up to 2,000 kWh of energy per month.

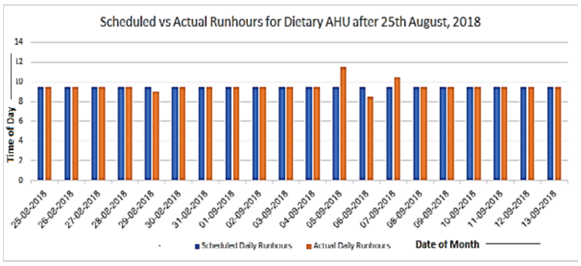

Figure 14: Actual vs Scheduled run hours of dietary AHU after recipe deployment.

CONCLUSION

Centralized cooling systems in India waste 40% of the 15 billion kWh of energy they consume because of inefficient system designs and equipment, and suboptimal operational practices. INR 5,000 Crore worth of energy can be saved in India by optimizing central cooling systems across industries. Smart Joules pay as you save model (Joule PAYS) guarantees commercial buildings a 15% reduction in energy in return for a high percentage share of the delivered savings under a five to a seven-year contract. The one-time exercise of improving the system design and selecting and installing state of the art energy-saving equipment alone won't be sufficient to maintain substantial savings throughout the contract period. Here lies the importance of Joule Recipes which continuously monitor system operation and takes the best possible decisions 24/7 eliminating energy wastage. In this paper, we have discussed the various applications of Joule Recipes upon a centralized air conditioning plant in one of the hospital buildings managed by Smart Joules. The results reveal that it contributed to 18-25% of the overall energy savings from the building which is equivalent to 3 - 3.5 lakhs of kWh for a year. The hospital segment alone presents an addressable annual revenue generation potential in excess of INR 550 Crore in India, of which at least 25-30% can be captured through the application of Joule Recipes across all the hospital buildings. Apart from the hospital buildings, centralized air conditioning of office buildings, malls and hotels is adding up to another 1,200 Crore. The application of Joule Recipes is not restricted to the hospital buildings, the "if this then that" algorithm can be applied across all the different kinds of air conditioning and process control applications such as low-pressure steam, hot water and compressed air. Joule Recipes holds the key to energy efficiency through continuous building energy optimization.

Joule Recipes serve the purpose of continuous building energy optimization bringing energy savings, but they are also paving the way for an artificial intelligence-based product of Smart Joules, Joule Mind. Joule Mind is a collection of services which derive insights out of the data to deliver actionable intelligence. The various Joule Recipes written by the energy engineers and domain experts will be continuously monitored and analysed by the Artificial Intelligence engine of Smart Joules DeJoule and they will be ranked based on effectiveness in terms of energy-saving potential. Going forward the Joule Recipes written now would become the fundamental building blocks of Joule Mind leading the user into an era of Artificial Intelligence.

NOMENCLATURE

Observable Parameter: Any data point collected from an HVAC asset or a sensor and available for a user.

Controllable Parameter: Any parameter which can be directly controlled through DeJoule.

Observation Interval: This is the number of previous data points a time series Joule Recipe will check for the condition statement.

Joule Recipe Action: One of the four control signals that can be generated by DeJoule on HVAC assets.

ACKNOWLEDGEMENT

We thank Mr. Arjun P Gupta (Founder & CEO, Smart Joules Private Ltd.) and Mr. Ujjal Majumdar (Director & COO, Smart Joules Private Ltd.) for their invaluable guidance and support for this work and on writing this paper. We also thank Mr. Aman Sapra (Developer Joule Recipe Service, Smart Joules) for the support in conducting the experiments for this study.

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ENERGY EFFICIENCY IN HVAC SYSTEM: CASE STUDY OF A HOSPITAL BUILDING COMPARING PREDICTED AND ACTUAL PERFORMANCE AND SHOWING IMPROVEMENTS THROUGH PERFORMANCE MONITORING

Prashant Kumar Bhanware[1], Pierre Jaboyedoff[2], Shirish Deshpande[3], Neelesh Shinde[4]

[1]*Indo-Swiss Building Energy Efficiency Project (BEEP)*
New Delhi, India
prashant@gkspl.in

[2]*Indo-Swiss Building Energy Efficiency Project (BEEP)*
Lausanne, Switzerland
pierre.jaboyedoff@effinart.ch

[3]*Energetic Consulting Pvt. Ltd. (ECPL)*
Thane, India
shirish.d@ecpl.co.in

[4]*Jupiter Hospital*
Pune, India
neelesh.shinde@jupiterhospital.com

ABSTRACT

It is well known that the HVAC (Heating, Ventilating and Air Conditioning) system accounts for the maximum energy consumption in most of the commercial buildings. In hospitals, HVAC system becomes even more important as the cooling (temperature and relative humidity setpoints) and ventilation (fresh air change rates) requirements are more stringent as compared to other commercial buildings. Hence, greater potential exists to save energy by incorporating energy efficiency measures in HVAC system.

The paper presents case study of a 350-bed multi-specialty hospital building in warm-humid climate (Pune), focusing on the HVAC system performance estimated through simulation at design stage, measured data post occupancy and impact of few measures identified during the monitoring. Energy efficiency measures include building envelope measures to reduce cooling load such as AAC block external wall, insulated roof and double-glazed window. HVAC system measures included optimum sizing of chiller, selection of energy efficient chillers with good part load performance, enthalpy recovery wheels for fresh air, use of condenser for reheating in air AHUs and heat pumps for water heating. Annual electricity consumption shows around half of the electricity is consumed by HVAC system and the EPI of the hospital is 136 kWh/m^2.y, which is very close to the predicted performance (130 kWh/m^2.y). The hospital gets a 4-star rating under BEE star rating for hospitals. During energy monitoring, operational improvements (increasing chilled water generation temperature, reducing condenser water temperature, change in heat pump control, etc.) in HVAC system were tried and later implemented; which resulted in further ~10% energy saving.

Keywords—hospital, energy efficiency, HVAC system, performance monitoring *(keywords)*

INTRODUCTION

In India, buildings contributed to ~33% of the total electricity consumption of 1130 TWh in 2017-18 (Energy Statistics, 2019). Projection done by NITI Aayog under different scenarios shows that the electricity consumption for the residential sector is expected to increase 6-13 times from 2012-2047 and 7-11 times for the commercial sector in the same time frame (IESS, 2047).

Energy performance index (EPI) (kWh/m^2.y) of commercial buildings is much higher as compared to residential buildings and also have a greater potential to save energy per unit area. Study conducted under ECO-III project showed that the average EPI of Indian multi-specialty hospitals was 378 kWh/m^2.y with a consumption of 13,890 kWh/bed.year (Kumar et al., 2010).

Heating, ventilating and air-conditioning (HVAC) system accounts for the maximum energy consumption in most of the commercial buildings. In hospitals, HVAC system becomes even more important as the cooling (temperature and relative humidity setpoints) and ventilation (fresh air change rates) requirements are more stringent as compared to other commercial buildings. The share of HVAC energy consumption in hospital buildings varies between 30-65% (ECO-III, 2009).

While there are many case studies available on energy efficient commercial buildings based on the energy simulations only; very few studies goes a step beyond and provide the simulated energy performance with the actual performance through detailed energy monitoring.

This paper presents case study of a hospital building, keeping a focus on HVAC system, and details out:

- Energy efficiency measures adopted in the building.
- Results of the building energy simulation during the building design.
- Comparison of predicted and actual energy performance
- Results of the performance monitoring of HVAC system

About the building

This hospital is a 350 bed multi-speciality tertiary care hospital (**Figure 1**). The building is situated in Pune which falls under warm-humid climate.

Figure 1: Hospital Building, Pune

Key details of the buildings are:

- Built-up area: 26,580 m^2 (excluding parking and service floor: ~9,500 m^2)
- Number of floors: 3 underground floors, 9 overground floors + 1 service floor
- Types of spaces: Technical areas like MRI, ICUs, Cath lab, OTs; patient indoor rooms and recovery rooms; restaurants, emergency rooms, etc.

Project timeline & key steps

- A design workshop for energy-efficient design with key project team members was organised at the design stage in February 2014. This workshop resulted in identification & selection of energy efficiency measures (EEMs) as well as building energy simulation to quantify energy savings.
- Construction of the building was completed in December 2016 and the hospital is functional since then. During the construction period, EEM proposals were further detailed out and the selection of HVAC system was done.
- Energy monitoring of HVAC system was done during November 2018 and May 2019 while the energy bills for 12 months (May 2018 to April 2019) were analysed.

Energy efficiency measures implemented

To improve the energy performance and daylight in the building, following measures were implemented:

- Roof insulation: 150 mm of RCC roof slab was insulated with 100 mm extruded polystyrene (XPS) which gives a U-value of 0.31 W/m^2.K.
- External wall: External walls were made of 150 mm AAC block with plaster on both sides, resulting in a U-value of 0.9 W/m^2.K.
- Glazing: The project team emphasised the importance of daylight in faster recovery of patients and clear glass was selected. However, double glazed units were selected to have a lower U-value of 2.8 W/m^2.K.
- Chiller sizing: Use of dynamic energy simulation software for chiller plant sizing instead of simplified calculation based on static design conditions. Installed chiller capacity is 560 TR (280 x 3 nos., 2 working + 1 standby).
- Chiller selection: High efficiency chiller with a COP of 5.92 with a very good part load performance (NPLV: 0.367), was selected.
- Enthalpy recovery wheels, with 75% effectiveness for both latent and sensible heat recovery, were integrated in the fresh air AHUs.
- Condenser water is used for reheating (refer **Figure 10**) the air in AHUs for maintaining the relative humidity. The backup hot water is provided by a heat pump system with a COP of 2.81.
- Free cooling: Patient floors have the provision of free cooling, which means if the the ouside air is suitable for space cooling, it can directly be supplied without passing through the cooling coil.

The system sizing calculation were done using HAP software and energy simulation of the building was carried out using DesignBuilder software to quantify the benefits of the integration of EEMs. The key results of the energy simulation were:

- Reduction in cooling system size: The cooling system size was reduced from 600 TR (before the design workshop) to 424 TR (after the integration of EEMs), which is a 29% reduction in the cooling system size (**Figure 2**).

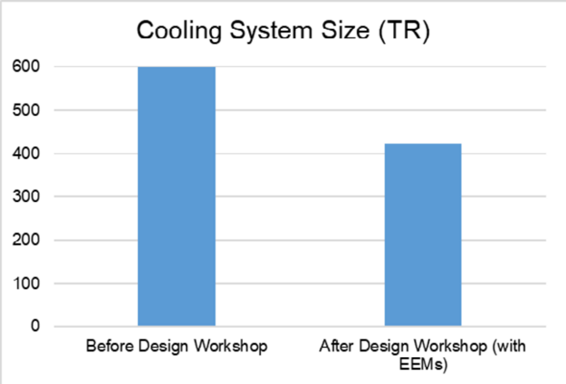


Figure 2: Reduction in cooling system size with EEMs

- Reduction in energy consumption: The energy performance index (EPI) was reduced from 154 kWh/m^2.y to 130 kWh/m^2.y (16% reduction) after considering EEMs in energy simulation (**Figure 3**).

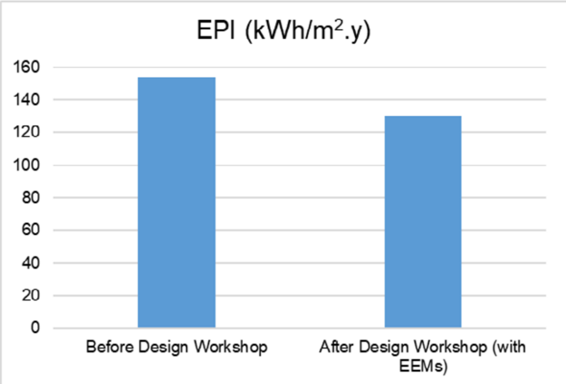


Figure 3: Reduction in EPI with EEMs

HVAC system monitoring

Energy monitoring for this building was focussed on HVAC system (**Figure 10**) as it contributes most (~60% as per calculations done during design workshop) to the total energy consumption. HVAC system monitoring was done during November 2018 and May 2019 while the energy bills for 12 months (May 2018 to April 2019) were collected. The monitoring included assessment of the HVAC system operation practice followed by the facility team and its impact on energy consumption. The utility equipments with significant impact on energy include chillers, cooling towers, chilled water and cooling water pumps, treated fresh air units and heat pumps. Performance of these utility equipments were evaluated during the study and compared with the design parameter and prevailing norms.

This paper discusses energy consumption pattern of the building and analyses the performance of the systems. It also tries to assess the impacts of trials or modifications carried on the systems.

For performance evaluation purpose, the following portable instruments were used, as mentioned in **Table 1**.

Table 1: List of instruments used during monitoring

S. NO	NAME OF INSTRUMENTS	MAKE	MEASUREMENT
1	Single CT power meter	MECO	Snapshot power measurement
2	Three CT Power Analyzer	Oracle	Power Data Logging
3	Three CT Power Analyzer	Krykard	Power Data Logging
4	Swing Psychrometer	JRM	DBT & WBT
5	Lux meter	TES 1332 A	Lux level
6	Surface contact type temperature sensor	Libratherm	Measurement of surface temperature on condenser water header
7	Ambient temperature + %RH sensor	Libratherm	Ambient Temperature + %RH
8	Ultrasonic Water Flow meter	GE	Data logging of Water flow through main header of condenser
9	Infrared Temperature Gun	Testo	Measurement of Envelope temperature

Key measurements done during the monitoring are listed below:

- Electrical system
  - All electrical panel meter readings on hourly basis
  - Power logging for chillers
  - Snapshot measurements of lighting and power distribution boards
  - Snapshot power measurements of cooling tower and pumps, heat pump
- Water Flow Measurements
  - Chilled water secondary flow logging
  - Cooling tower flow measurements
  - Heat pump flow measurements
- Treated Fresh Air Units
  - Power, airflow across energy recovery wheels
  - Electrical power for fans
  - Temperature and RH measurements

In addition some specific measurements were done:

- To measure the impact of reduced condenser water temperature in chiller performance
- To evaluate the combined efficiency of two VFD based chillers, when operated at part load as compared to one chiller operation in full load
- To measure the performance of cooling tower when two cooling towers were operated as compared to one cooling tower for similar cooling loads
- To measure the effectiveness of treated fresh air (TFA) unit

RESULTS AND DISCUSSIONS

Overall energy performance

The electricity consumption data for 12 months (May.18 to Apr.19), collected during the monitoring, is shown in **Figure 4**.

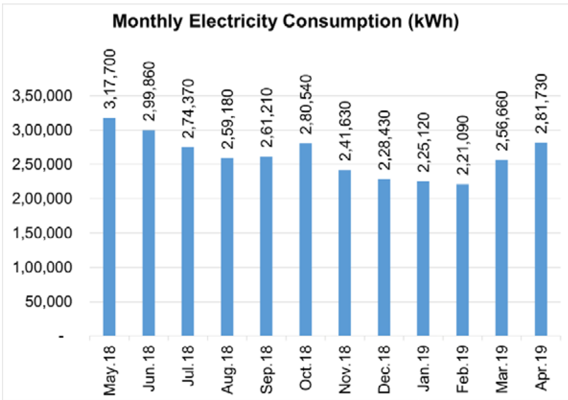
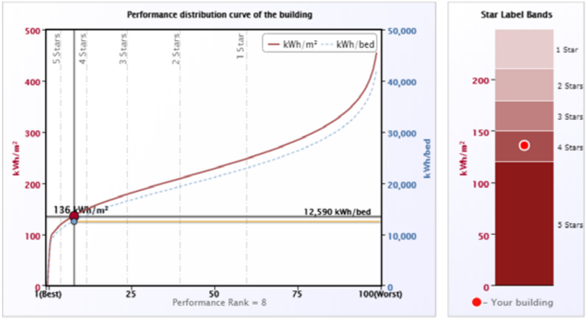


Figure 4: Actual monthly electricity consumption

During the monitoring period, two recovery floors were not operational, resulting in operational beds as 250 and the overall operational area as 2,49,000 ft^2. The annual energy consumption of this hospital was 31,47,520 kWh/y, resulting in an EPI of 136 kWh/m^2.y and 12,590 kWh/bed.y. Simulated EPI did not account for sewage treatment plant, outdoor lighting and basement ventilation; this would add ~8-10% in the EPI. Overall, simulated EPI (130 kWh/m^2.y) is in very good agreement with the actual EPI (136 kWh/m^2.y).

The energy performance of the building was evaluated under the BEE star rating of hospital using the ECObench tool, which is the energy benchmarking and rating assessment for hospitals. The results (**Figure 5**) show that this buildings qualifies for a 4-star rating.



Parameters	Measured	Benchmark
Electricity Used (kWh)	3,147,520	5,292,889
EPI (kWh/m²)	136	229
EPI (kWh/bed)	12,590	21,172

Building Performance Rank: 8

★ ★ ★ ★

Figure 5: Results from BEE's Benchmarking & Performance Rating Tool for Hospitals

The break-up of energy consumption (**Figure 6**) shows that the HVAC system consumes 50% of the total energy consumption, and chillers contribute maximum (19%). Chiller plant hydronics mainly includes primary chilled water pump, secondary chilled water pump, cooling tower pump and cooling tower fans. Other HVAC mainly includes hot water system, cold storage and basement ventilation.

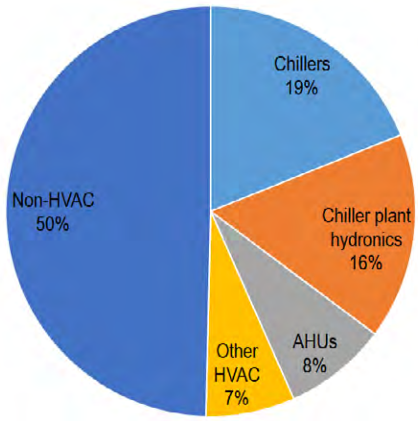


Figure 6: Break-up of energy consumption

HVAC system monitoring results

Impact of reduced condenser water temperature in chiller performance

During the winter monitoring in November 2018, it was observed that the cooling water (input to the condenser of the chiller) temperature was kept to 27-28˚C considering the reheating requirements. However, it was possible to achieve a cooling water temperature of 21-24˚C from the cooling tower. The measured data show that, with reduced water temperature, average chiller energy consumption during winter was reduced from 1646 to 1434 kWh/d, while in summer it reduced from 1972 to 1693 kWh/d

(**Figure 7**). This resulted in chiller energy saving of 13% in winter and 14% in summer.

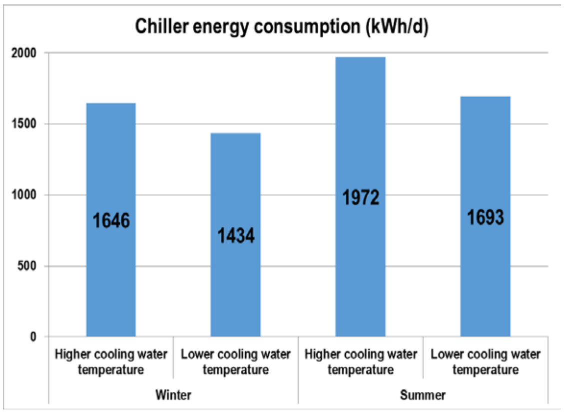


Figure 7: Impact of reduced condenser water temperature on chiller energy consumption

Chiller part load parallel operation vs single chiller full load performance

Chillers installed are equipped with VFD, thus the part-load performance of the chillers is better than full load performance. The performance comparison was done by running two chiller in part load and one chiller in full load. In Case 1, two chillers, two primary chilled water pumps, two secondary chilled water pumps, two cooling water pumps and two cooling towers were operational. In Case 2, one chiller, one primary chilled water pump, two secondary chilled water pumps, two cooling water pumps and two cooling towers were operational.

The average chiller performance measured in Case 1 was 0.41 kW/TR while in Case 2, it was 0.46 kW/TR (**Figure 8**). This shows that the chiller performance in Case 1 was 12% better as compared to Case 1.

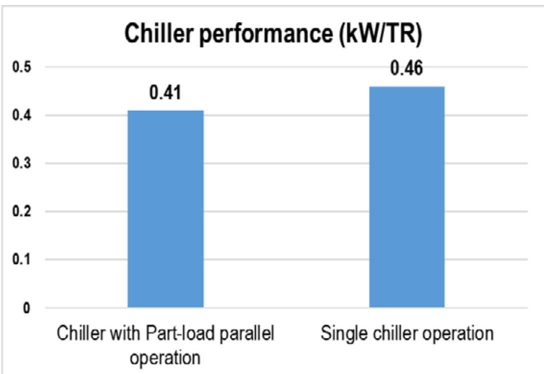


Figure 8: Chiller part load parallel operation vs single chiller full load performance

Cooling tower performance

The hospital has two cooling towers installed of capacity 349 TR each. Both the cooling towers are operated with one chiller operation or two chiller operation. The measurements were done for two cases: Case 1, when two cooling towers are operational and Case 2, when only one cooling tower was operational.

During Case 1, the heat load on cooling tower 1 and cooling tower 2 was 104 TR and 103 TR respectively, as against rated capacity of 349 TR. The key results were:

- The cooling tower approach was measured to be 1.4˚C and 2.1˚C for cooling tower 1 and cooling tower 2, respectively, while the design approach is 3˚C.
- The water-to-air ratio of the cooling tower 1 and 2 were 0.36 and 0.46 respectively, while the design vaue is 0.67.
- Effectiveness for cooling tower 1 and 2 were 71% and 61%, respectively.

During Case 2, the heat load on cooling tower was 234 TR, as against rated capacity of 349 TR. The key results were:

- The cooling tower approach was measured to be 3.7˚C and water-to-air ratio was 0.90.
- Effectiveness for cooling tower was 49%.

TFA unit performance

The facility has treated fresh air units installed for supplying fresh air. Measurements were carried out of the TFA during the study. The TFA had heat recovery wheel to cool the fresh air using the exhaust air. Chilled water was used for further cooling of the fresh air (**Figure 9**).

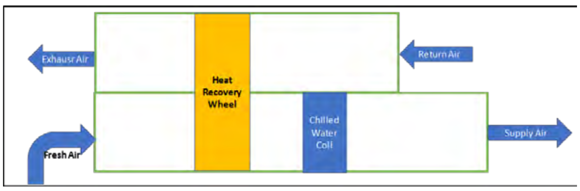


Figure 9: Schematic of TFA unit

Measurements were done to calculate the effectiveness of heat recovery wheel (HRW) installed in the TFA unit. Measured data of temperature of return air before HRW as 29.4˚C, fresh air as 33.3˚C and fresh air after HRW as 30.0˚C results in an sensible effectiveness of HRW as 85%.

Further energy saving opportunities

Presently, when only one chiller is operational, two cooling towers are operated to keep condenser water temperature low and therby chiller energy consumption. Cleaning of cooling tower fills and

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descaling of basin and cooling water circuit will help achieve the designed performance. Potential energy savings by this measure are 48,180 kWh/y.

For a significant duration (~4500 hous), ambient temperature and humidity in Pune remains below the design conditions. This gives an opportunity to run cooling tower fans on part-load but presently, there is no VFD for cooling tower fans. Installing VFD for cooling tower fans will help optimize it's energy consumption. Potential energy savings by this measure are 49,500 kWh/y.

Cooling water pumps flow rates can also be optimized as per ambient conditions but they also do not have VFDs. Installing VFD on cooling water pumps (3 nos.) will help optmize the flowrates and reduce energy consumption. Potential energy savings by this measure are 22,500 kWh/y.

CONCLUSION

Good quality case studies based on monitored energy performance are needed for promoting energy efficiency in buildings. The paper presents case study of a hospital building at Pune and cover:

- Energy efficiency measures adopted in the building
- Results of the building energy simulation during the building design
- Methodology and results of the HVAC system performance monitoring
- Results of specific measures for HVAC system and identification of further energy saving opportunities

Energy efficiency measures (EEMs) for this building includes roof insulation, AAC block external walls, double glazed windows, chiller sizing using dynamic energy simulation software, high efficiency chiller with very good part load performance, enthalpy recovery wheels, condenser water for reheating and free cooling.

The actual EPI (136 kWh/m^2.y) of this building is very close to the predicted EPI (130 kWh/m^2.y). The monitoring of this building was focussed on HVAC system as it consumed maximum electricity (50% of the total) and has maximum saving potential as well. HVAC system components were monitored and their performance were compared with the design values. While some of the operational improvements were implemented during monitoring, further energy saving opportunities were identified with energy saving potential of 1,20,000 kWh/y.

There is a need to have many such case studies. This would help in motivating builders / developers and other building sector professional to adopt energy efficiency measures in their projects.

ACKNOWLEDGEMENT

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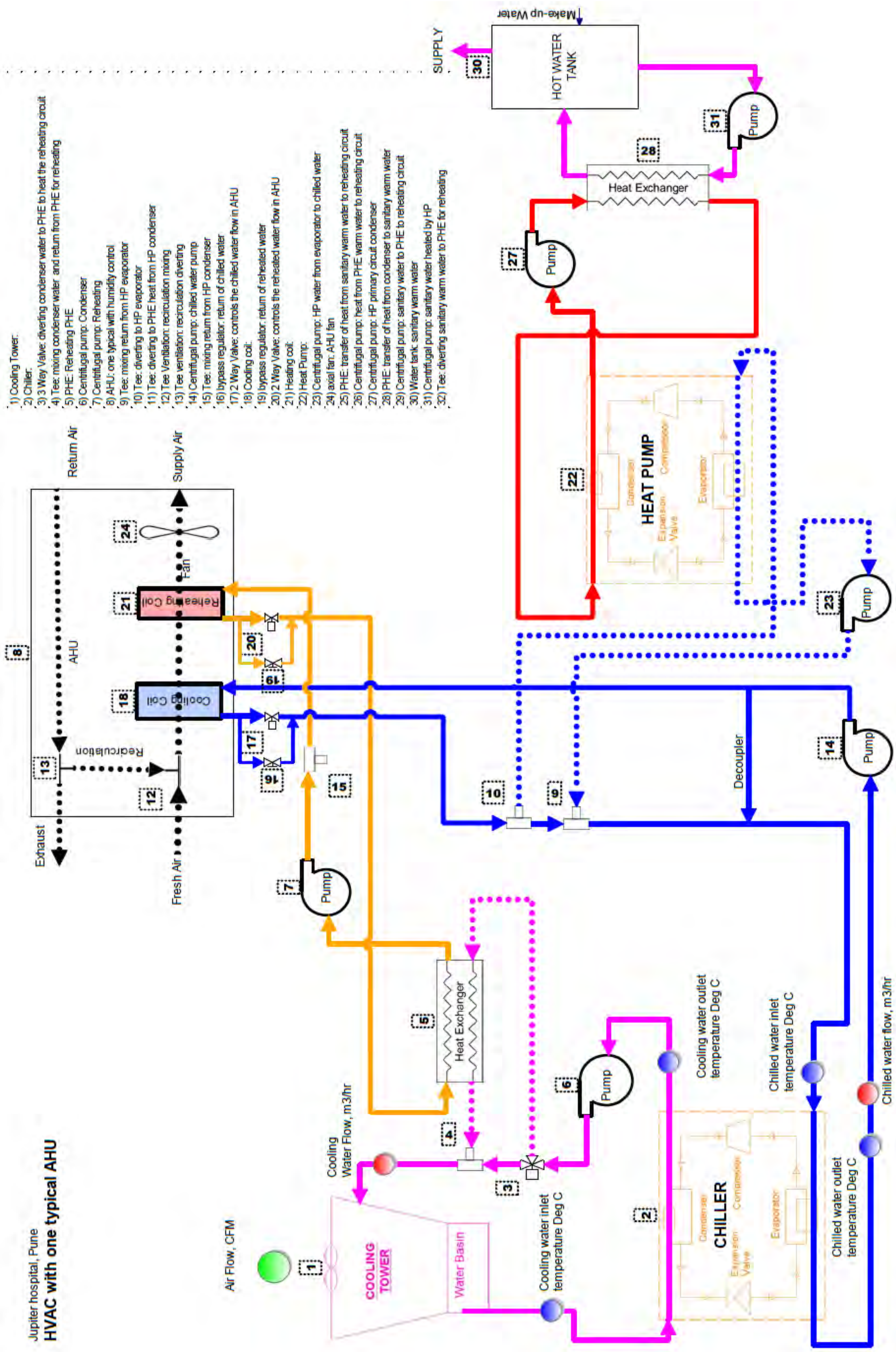

Figure 10: Simplified HVAC system schematic with one typical AHU and key measurement points

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ASSESSING CONSUMERS' BEHAVIOURS, PERCEPTIONS AND CHALLENGES TO ENHANCE AIR CONDITIONER'S ENERGY EFFICIENCY

Apurupa Gorthi [1], Shikha Bhasin [2], Vaibhav Chaturvedi [3]

[1]*Technology, Finance and Trade*
Council on Energy, Environment and Water
New Delhi, India
apurupa.gorthi@ceew.in

[2]*Technology, Finance and Trade*
Council on Energy, Environment and Water
New Delhi, India
shikha.bhasin@ceew.in

[3]*Technology, Finance and Trade*
Council on Energy, Environment and Water
New Delhi, India
vaibhav.chaturvedi@ceew.in

ABSTRACT

With growing presence of air conditioners (AC) in Indian residences, anticipated to grow over eleven-fold in the next twenty years, end-users constitute an important part of the AC value chain. Emissions during the operational lifetime of the ACs, both as a consequence of electricity use and high global warming potential (GWP) refrigerant emissions, constitute a substantial share of India's projected greenhouse gas emission profile. A significant opportunity to reduce these emissions is available if households adopt better AC use practices. Recognising this, the Ministry of Power (Government of India), recently provided an advisory to manufacturers to set a minimum temperature of 24°C as the default during sale of residential ACs. The Bureau of Energy Efficiency (BEE) also launched a consumer awareness campaign, 'AC@24°C or more', to encourage use of ACs at setpoints above 24°C among residential consumers. Since the launch of this campaign there has been no assessment of its impact on consumer behaviours. Through a baseline assessment across four cities and 432 households, this study finds that about 73 percent of consumers used their residential ACs at a temperature of 23°C or lower. However, AC use duration was found to be an average 8 hours with over 70 percent of the households using ACs for six months or less. These findings indicate to a tendency to employ conservative practices for AC use however adoption of lower setpoints for AC use. Findings from this study can be useful in informing future BEE awareness campaigns towards widespread adoption of higher setpoints for AC use.

Keywords—residential air conditioners, consumer behaviour, energy efficiency, electricity conservation.

INTRODUCTION

The rise in residential air conditioner (AC) penetration in India and its impacts on electricity consumption and resultant emissions are well studied (Chaturvedi and Sharma, 2014; Phadke, Abhyankar and Shah, 2014; Kumar *et al.*, 2018; Ozone Cell, 2019; Somvanshi, 2019). The residential sector in India is already a major consumer of electricity, estimated at constituting a fourth of the total generated electricity for 2016-17 (PwC, 2019). The India Cooling Action Plan (ICAP) states that with space cooling demand (residential and commercial) expected to grow eleven times the current demand by 2037, energy demand in this sector may increase by nearly 4.5 times the current use (Ozone Cell, 2019). With such an increase, by 2030 residential cooling alone could have electricity consumption equivalent to current total residential connected load (Somvanshi, 2019). Consequentially, the residential sector's electricity demand is expected to supersede that of the industrial sector (NITI Aayog, 2015). While the ICAP states that stringent policy measures can decrease electricity demand by 30 percent by 2037, implementation of these policies are at a nascent stage and their impact is yet to be measured (Ozone Cell, 2019).

An integrated approach to optimise electricity consumption of residential ACs comprises of three main components (Ozone Cell, 2019):

- Design and engineering of energy efficient ACs. For example, the energy star rating programme.

- Adoption of good service practices for ACs. For example, minimising refrigerant leakage and recovery.
- Efficient usage of ACs by end-users. For example, higher temperature setpoint for ACs.

Addressing the first of the three approaches, the Bureau of Energy Efficiency's (BEE) Standards and Labelling (S&L) programme has successfully created a market for energy efficient star labelled ACs in India (CLASP, 2015). A myriad of programmes for service technicians in the residential AC sector have focused on training them on good servicing practices, aimed at minimising operational life emissions (Sridhar and Chaturvedi, 2017). Irrespective of the success of these efforts, improper use of the ACs by end-users can have a significant impact on their energy efficiency and consequent operational emissions (Chaturvedi *et al.*, 2015; Somvanshi, 2019).

Addressing the need to limit operational life emissions of the AC, consumer driven energy conservation practices have been an area of focus for the Ministry of Power and the BEE. Using ACs at a high setpoint of 24°C to 26°C has found to show annual energy savings between 20 to 28 percent (Ozone Cell, 2019). Taking this forward, the Ministry of Power issued an advisory to manufacturers to set AC's default temperature at 24°C during sale (PIB, 2018). Further, to encourage wide adoption of higher AC setpoint, in June 2018, BEE released a statement encouraging commercial establishments like hotels, shopping malls etc. to set their cooling equipment at 24°C or more (BEE, 2018). An online campaign was launched on Twitter and Facebook called 'AC@24°C or more' to create awareness on use of AC at higher setpoints.

In the last year various modes of information dissemination were used by the BEE to encourage widespread adoption of higher AC setpoints. Newspapers published information on this campaign with potential gains for consumers from this initiative (e.g. Kumar, 2018; PTI, 2018). Additionally, BEE published a webpage with Frequently Asked Questions with information on potential savings as well as issuing directives to government offices to set their temperatures to 24°C (PIB, 2018). During the summer of 2019, BEE's Twitter page periodically posted information related to economic and environmental gains from higher temperature of use (see for example, BEE, 2019a). The National Radio network was also used as a platform to disseminate this information in 2019 (BEE, 2019a).

With the summer of 2019 coming to a close and two years of this campaign being implemented, there is a need to understand its impact on residential AC users. Data on current preference for AC setpoint and hours of use can help inform future awareness campaigns by the BEE. Through this baseline assessment of four non-metropolitan Indian cities, we aim to present current household behaviours in relation to AC use temperature.[1] From this perspective we aim to determine the following:

- What is the AC use duration (hours/ day, months) during summer months in India?
- What is the preferred temperature set point for AC use among households?
- How do households perceive the impact of AC temperature on its electricity consumption?

METHODOLOGY

The data for this study was gathered using a door-to-door survey conducted across four Indian cities (listed in **Table 1**). All cities with a population of 10 lakh or more as per Census 2011 data were classified into zones of North, South, East and West and one city from each zone was randomly picked. Three of India's five climate zones were represented by these cities (US-AID Eco-Project III, 2011) (see **Table 1**).

City	Zone	Climate Zone	Summer temperatures
Meerut	North	Composite	27-43°C
Dhanbad	East	Composite	27-43°C

[1] The four cities in this analysis were randomly picked and it is only by chance that they are not large metropolitan cities.

Vadodara	West	Hot-Dry	20-45°C
Madurai	South	Warm-Humid	25-35°C

Table 1: City represented in this paper and their climate profile (Source: US-AID Eco-Project III, 2011)

A total of 432 households were surveyed from across the four cities with equal number of households represented from each city. Within each city six municipal wards were randomly picked from a list of wards in the city. The list of wards was obtained from the local municipality by the survey enumerators. Through manual survey of each ward, housing localities were identified and three of these were picked at random as starting locations for the survey. A total of eighteen households were surveyed in each of these wards. Enumerators began the survey with the first house to their right and skipped five housing structures for the next interview.

Respondents considered for the survey were required to own at least one AC and should have made decisions related to its purchase and servicing. Additionally, the following guidelines were followed in selecting respondents for the survey:

- Respondents were required to be at least 21 years of age and must continue to live in the current dwelling until January 2020.
- The AC is at least two years old and is not on a purchase warranty.

The baseline questionnaire covered a range of concepts including AC purchase, energy star label programme, AC use patterns and servicing practices and awareness (See Annexure). This paper is based on an analysis of thirteen data points focusing on AC use patterns and ownership (Q 207 to Q 212). Survey questions did not directly capture end-user perceptions towards the ‘AC@24°C or more’ awareness campaign.

The survey was conducted at the start of summer (between May 24 and June 12, 2019) targeting the start of AC use in the four cities. The survey was conducted in the most widely spoken regional language in each city, viz. Hindi for Dhanbad and Meerut, Gujarati for Vadodara and Tamil for Madurai. A Computer-Assisted Personal Interview (CAPI) tool was used to survey households. For this particular study we employed the online software, SurveyCTO to administer the survey and record responses.[2]

DISCUSSIONS AND RESULT ANALYSIS

Findings from the field survey of 432 households equally spread across Dhanbad, Meerut, Madurai and Vadodara attempted to understand AC use duration and temperature setpoints.

AC Penetration in Surveyed Households

The average number of ACs per household was 1.14, while a little over ten percent of the households reported owning more than one AC. A pan-India analysis by Sachar, Goenka and Kumar, (2018) reported a higher estimate of 1.7 ACs per household, while the National Sample Survey (2001) reportedly found 1.2 ACs per household (Chunekar and Sreenivas, 2019). Economic growth and sustained electricity access have been noted to be main drivers of AC ownership, thereby making ACs more prevalent in metropolitan cities (CEEW, NRDC, TERI and IGSD, 2013; Chunekar, Varshney and Dixit, 2016). Therefore, lower AC penetration noted across the four cities in the current study may be attributed to their non-metropolitan status.

AC Use Duration

Number of months of AC use.

On average, AC use spanned 5 months in a year. About 74 percent of the respondents indicated AC use for 6 months or less, with close to a quarter of the respondents stating 4 months of AC use. Further,

[2] SurveyCTO is a computer-assisted personal interview tool that was developed in India to assist with quantitative and qualitative surveys. Further information on the software can be found here.

56 percent of the respondents used their ACs for 4 to 6 months in a year. Average number of months of use did not vary significantly by climate zones. However, within the variability observed, a significant proportion of respondents indicated 3 or 4 months of AC use in Vadodara whereas the other three cities were skewed towards higher number of months of use **(see Figure 2)**. These trends show that AC use is restricted to less than half the year for a majority of households.

It is important to note the following about AC use among Indian households to further enhance energy conservation practices. Many households were found to start their AC use only after outside temperatures reached a minimum threshold of 31-32°C (Somvanshi, 2019). Further, Sachar, Goenka and Kumar, (2018) noted adaptive thermal comfort practices like use of fans with AC by a majority of households surveyed. Both of these point to an existing adaptive thermal comfort practice among residential AC users in India. This presents a significant opportunity to make adaptive thermal comfort a more pervasive practice among households' through awareness.

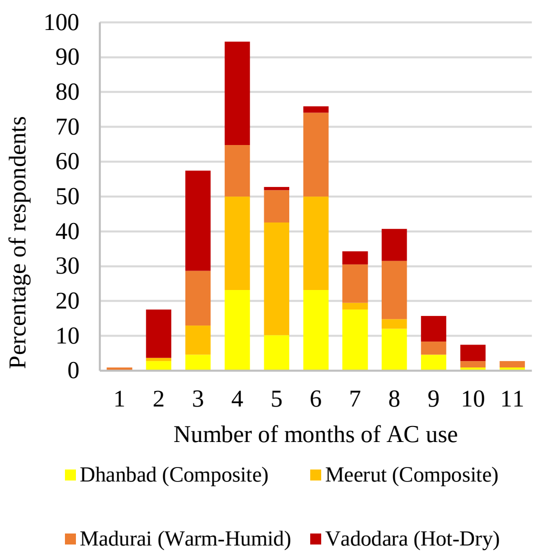

Figure 1: Number of months of AC use by proportion of respondents (N = 432). (Source: CEEW analysis, 2019)

Hours of AC use.

Respondents were also asked to record their daily hours of AC use during peak summer months such as May, June and July and other months of summer such as April or August. Average duration of AC use was 8 ± 3 hours for peak summer months across all four cities. For other summer months, when outside temperatures were expected to be comparatively lower, average runtime reduced to 4 hours at the same level of variability.

A city wise comparison yielded the following observations. For peak months of summer, Meerut showed the highest runtime average at ~10 ± 3 hours and the least was observed for Madurai at ~7 ± 3 hours. For other summer months, runtimes were generally half of that in peak summer months. As per this, average runtime was again the highest in Meerut and lowest in Vadodara as indicate in **Figure 3.** Further, substantial variability was observed as depicted in **Figure 3,** perhaps pointing to individual preferences in AC use duration. For other summer months, the variability could be explained by the fact that over 80 respondents, mostly from Vadodara, reporting no AC use.

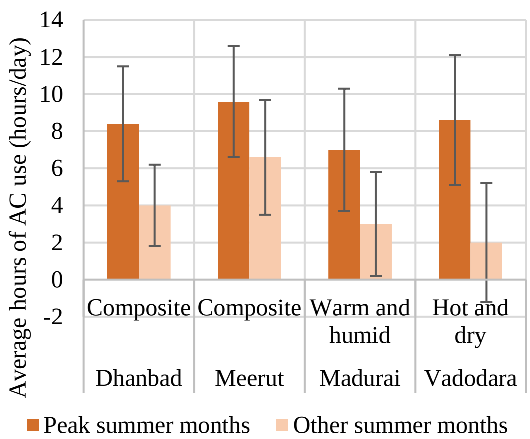

Figure 2: Number of hours (hours/day) of AC use for peak summer months and other summer months for the four cities in terms of their means and standard deviations (N = 432). (Source: CEEW Analysis, 2019)

Annual runtimes were calculated for each city using average months of AC use and considering average runtime for peak summer months **(Table 3)**.

City	**Climate zone**	**Mont hs**	**Hours of use**	**AC duration (hours/ year)**
Dhanbad	Composite	6	8.4	1512
Meerut	Composite	5	9.6	1440
Madurai	Warm and humid	6	7	1260
Vadodara	Hot and dry	5	8.6	1290

Table 2: Annual AC use duration (Source: CEEW analysis 2019)

A nuanced calculation of this was not possible due to limited data collected for this. Highest AC use duration was observed for Dhanbad and Meerut (composite) followed by Vadodara (hot and dry) and Madurai (warm and humid), respectively. In comparison, Sachar, Goenka and Kumar, (2018) reported average annual runtime of 1635, 1355, and 1421 for composite, hot-dry, and warm-humid, respectively. However, these were averages of more than one city under each climate zone, a majority of which were large metropolitan cities. Therefore, similar to appliance ownership, the lower values of AC run-times obtained in our analysis may be attributed to the non-metropolitan status of the four cities.

Dhanbad and Meerut with their composite climate showed higher annual AC use hours than Madurai and Vadodara, also observed by Sachar, Goenka and Kumar, (2018) for the climate zones these cities represent. However, contrary to Sachar, Goenka and Kumar, (2018), warm-humid Madurai showed lower runtime relative to hot-dry Vadodara. This may be due to differences in economic status of the households from the two cities. Anecdotal evidence from the field points to households using ACs for brief periods, with most relying on the use of fans. Similar observations were also reported by Chunekar and Sreenivas, (2019)

AC setpoint – use and perceptions.

Another aspect of AC use assessed was temperature setpoint for peak summer months and other summer months. Overall, average AC setpoint for peak summer months was 21 ± 3 °C with a one degree increase for other summer months at the same variability. While preference for higher setpoints was not apparent from the average values, a small but significant difference was observed in setpoints as shown in **Figure 4.**

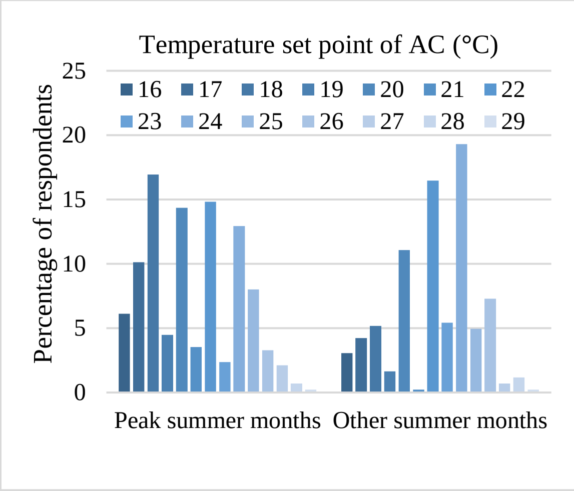

Figure 3: Percentage of respondents using AC at various temperatures for peak summer months and other summer months (N = 425 for peak summer months and N = 420 for other summer months). (Source: CEEW analysis 2019)

Similarly, at a city level, we observed a general decline in preferred temperatures between peak and other summer months with the exception of Meerut **(Figure 5)**. This anomalous trend cannot be explained as temperatures were not noted for specific months. It is possible that the use of broad categories for summer months may have led to respondents confounding one with the other.

In light of the recent BEE awareness campaign related to higher temperature setpoints, respondents were asked if AC temperature setting had an impact on its energy consumption. About 46 percent of the respondents indicated that it did, whereas 28 percent of the respondents indicated that they did not know. While this is significant, there was no data on respondents understanding on how AC temperature affected energy consumption. However, it may be useful to note that about 73 percent of consumers indicated using AC at a temperature of 23°C or lower both during peak summers and other summer months.

The following, however, provided some insight into how households perceived AC temperature in the context of good use practices. When asked examples of good maintenance practices for ACs, a small proportion of respondents pointed to using a low temperature and some others pointed to using the AC at a constant temperature.

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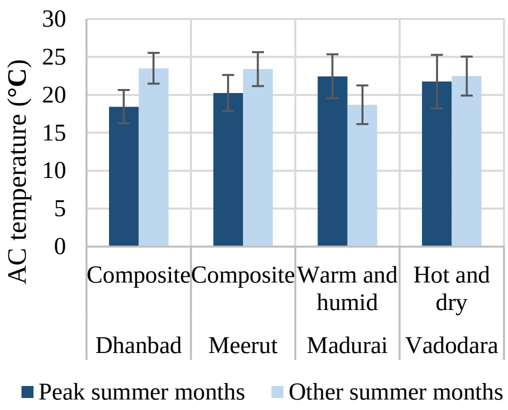

Figure 4: Temperature of AC (°C) use for peak summer months and other summer months for the four cities in terms of their means and standard deviations (N = 432). (Source: CEEW Analysis, 2019)

These responses related to temperature of use was from a fraction of respondents (4 percent), however, it is significant in that it may be indicative of prevalent misconceptions.

Respondents were not explicitly asked if they were aware of the BEE's 'AC@24°C or more' campaign. However, their current use practices point to the possibility that they are either not aware or not inclined to adopt this practice. Notably, adopting higher AC temperature involves no additional investment, is easy to perform and can be performed regularly (Moore and Boldero, 2017). 'Continuous' behaviours of this kind can be inculcated by appealing to self-interest of consumers through the medium of education (Moore and Boldero, 2017). To this end, BEE's twitter campaign has emphasised both on energy savings as well as health impacts of using 24°C or more for ACs. However, the lack of implementation of this practice suggests the need to increase efforts both in frequency and medium for these awareness campaigns.

CONCLUSIONS

This paper aimed to provide a baseline assessment of residential AC setpoint temperatures in the specific context of BEE's recent 'AC@24°C or more' awareness campaign. Households across the four cities of Dhanbad, Meerut, Madurai and Vadodara were found to use ACs for less than six months in a year, for about 8 hours a day at a temperature of 21 °C during peak summer months. Further, a significant decrease in hours of AC use was noted for peripheral summer months with households running their ACs at higher temperatures. This presents a significant opportunity to promote energy conservation behaviours among households. While the BEE used various media for their awareness campaign, the main medium for awareness was their twitter page. With households continuing to use a lower set-point for their ACs, it is imperative that the BEE to expand the 'AC@24°C or more' awareness campaign using accessible informational platforms such as print-media, TV, among others.

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ANNEXURE: SURVEY QUESTIONNAIRE

Project Name : Consumer Behaviour Survey for Urban Households	**Questionnaire**	**May/ 2019/ FTU**

Centres	Dhanbad (Jharkhand :1 Meerut (Uttara Pradesh) : 2 Vadodhara (Gujarat) : 3 Madurai (Tamil Nadu) : 4
Name of respondent	
Sex	**Male 1 Female 2**
Address	______________________ ______________________

Name of Interviewer (INT): ______________________

Name of Supervisor (SUP): ______________________

FIELD CONTROL INFORMATION												
	D	**D**	**M**	**M**	**Y**	**Y**	**START TIME**					
FIRST VISIT INTV DATE					**1**	**3**	**END TIME**					
SECOND VISIT INTV DATE					**1**	**3**	**START TIME**					
							END TIME					
SUPV.CODE					**INV.CODE**		**CHECKED CODE**					
ACCOMPANIED CALL	**Y 1 N 2**		**BY:CODE**				**SIGN**					

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SPOT CHECK	**Y 1 N 2**	**BY:CODE**						**SIGN**	
BACK CHECK	**Y 1 N 2**	**BY:CODE**						**SIGN**	
SCRUTINY:FIELD	**Y 1 N 2**	**BY:CODE**						**SIGN**	
ANALYSIS OBSERVATION: EXTENT OF PROBLEM					**NO /MINOR 1 MILD 2 SEVERE 3**				
SCRUTINY : ANALYSIS			**YES ....1 NO.........2**					**BY :**	

Namaskar
My name is ____________. I work with Sigma Research and Consulting, a social research organisation that conducts surveys on health, education, energy etc in India. Your household has been randomly selected to participate in a short survey. The survey is a part of a study by the Council on Energy, Environment and Water (CEEW). The survey has questions on household air conditioner purchase and use. This survey, being conducted in approximately 400 households, will be used to explain the current levels of consumer awareness and behaviours related to AC usage in India.

This survey will happen in two phases, the first is in May 2019 and the second in October 2019. We will also be sending you some text messages in between the two surveys. Information collected for the survey is confidential and will be used for research purposes only.

If you have any questions, you can ask us. The interview will take approximately 30 minutes.

Do you give your consent for the interview?

Before we start the survey, we would like to check for the following:

Q No	Question	Coding Category	Skip
S1.	Do you own an air conditioner?	Yes.. 1 No..2	
S2.	Have you used this air conditioner for at least two years (as of April 2019)?	Yes.. 1 No..2	
S3.	Will you continue to live in the same house until November 2019?	Yes.. 1 No..2	
S4	Have you ever had at least one general servicing done of your AC?	Yes.. 1 No..2	
S5.	Were you one of the key decision makers involved in deciding about your AC purchase?	Yes.. 1 No..2	
S6.	Are you one of the key decision makers involved in the maintenance (servicing-related decisions) of your AC?	Yes.. 1 No..2	
S7.	Do you agree to participate in two rounds of this survey-one today, and one in October 2019?	Yes.. 1 No..2	

If answer to question 5 or 6 is no, please request to speak to the relevant household member till those can also be marked as 'yes'.

If the answer to any of the other questions (1, 2, 3, 4, and 7) is no, please thank them for their time and move to next household.

If the answers to all the above questions are yes, please share the consent form with them.

A. Meta Data

101	Household ID ___________________	

102	ID of Interviewer ______________	
103	Name of Interviewer ______________	
104	ID of Supervisor __________________	
105	Name of Supervisor ___________________	
106	Date of Interview ________________	
107	Interview start time ________________	
108	Interview end time _________________	
	Geographic Information	
109	City ________________	
110	Ward_________________	
111	Locality_________________	

112	Full Address____	
113	Mobile Contact Number ____________________________	
114	GPS Latitude_________________________	
115	GPS Longitude___________________________	

Baseline Questionnaire: HFCI&R Consumer Awareness Survey

B: Consumer Information

201	Name _______________________	
202	What is your Age ________________(in completed years)	
203	Gender Male ....1 Female...2	
204	What is the Highest degree earned by you ?	

No formal schooling	1
Up to 5th standard	2
5-10 standard	3

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	10-12 standard	4	
	Graduate	5	
	Diploma	6	
	Masters and above	7	
205	hat has been your field of study?		
	Chemistry		
	Economics		
	Physics		
	Engineering		
	Urban/ development planning		
	Architecture		
	Electricals		
	Others (please specify) ___________________		
206	What is your occupation? GIVE CODES _________________		

In the case of there being multiple ACs within a household, please request the respondent to answer all remaining questions for any one particular AC that most closely represents the following:

- ✓ **At least two years old and no older than five years**
- ✓ **It is not a rented AC**
- ✓ **It is not still under company's purchase warranty period for servicing**
- ✓ **It is an AC you frequently use**
- ✓ **You were among the primary decision makers during the AC's purchase**
- ✓ **You are among the primary decision makers for your AC's servicing**

207	What was your expenditure on electricity for:		
	1	The month of April 2019? _______________	
	2	The monthly average over the past year? ___________________	
208	Do you have a separate meter connected to your AC?	Yes .... 1 No 2	

209	How substantial do you think is your AC's contribution to your monthly electricity bill in summers?	Very small ....1 Small...2 Substantial ....3 Large...4 Not sure/ Don't know 99	

210. Please indicate the following about your AC usage:

Note: Interviewers have to explain the distinction between the last two columns in this question. Column three asks what the respondent thinks is the ideal temperature at which the AC should operate for best cooling and operation of the AC, while the last column asks for the usual temperature set by the respondent for room cooling.

Months	Hours of AC use per day in your household during specific months?	What temperature does the AC need to be set at for optimal cooling during specific months?	What temperature do you set your ACs at during specific months?	
Peak summer months (e.g. May to July)	10.1__________	10.3 ________________	10.5 ________	
Other summer months (e.g. April, August, etc.)	10.2 ________	10.4 ____________________	10.6 __________	

211	How many months of the year do you use your AC?	☐☐	
212	Do you think the level of temperature setting effects the energy consumption of the AC unit?	Yes: 1 No: 0 Don't know: 99	

213	Are you aware of the star labelling programme?  	Yes 1 No 2	
214	Describe your level of trust towards the star labelling programme to correctly indicate the AC's energy performance	Highly trustworthy .... 1 Trustworthy .... 2 Not trustworthy 3	
215	What are your thoughts on the usefulness of the star labelling programme?	Very useful .... 1 Useful .... 2 Not useful 3	
216	Did you want to purchase a high star labelled AC?	Yes .... 1 No 2	
If 'no' (0) to B16, please skip to C1. **If "yes" (1), pleasego to B17.**			
217	Did you purchase a 4 or 5 star labelled AC?	Yes.. 1 No 2	
218	Please indicate why you did not purchase a 4 or 5 Star labelled AC?:	Cost was much higher than the next best alternati .... 1 Cost was marginally higher than the next best alternative .... 2 Unsure about its effectiveness – there is a trust deficit .... 3 My use of that AC is very low, compared to the higher capital cost difference, so didn't seem worth the investment .... 4 Other reasons (SPECIFY) 5	

C: Purchase Decisions

301	Please rank five of the most important sources of information you used to make decisions on purchasing your air conditioner?	Newspaper or magazine Advertisement.. 1 Star rating sticker/ information .... 2 TV commercial .... 3 Radio commercial 4	

		Billboard.. 5 Online advertisements (social media, general websites) .... 6 Online/social media reviews.................. 7 company websites.................................. 8 Salesperson.. 9 Friend, Neighbour, relative or co-worker... 10 Previous experience.............................. 11 Others (specify)________________... 12	
302	Please rank five of the most important attributes that you considered when buying your AC :	Brand .... 1 Country of brand... 2 Country of manufacture................................. 3 Aesthetics and design features .... 4 Energy Star rating .... 5 Tonnage .... 6 Refrigerant .... 7 Wiring (aluminium, copper, etc.).................... 8 Other components (such as compressor, etc.)............................. 9 Pricing/ cost of the AC .... 10 Incentives like festival offers, discounts, EMIs etc... 11 Warranty of product...................................... 12 Servicing/maintainace warranty or contract... 13 Maintainace cost.. 14 Others (please specify) 15	

Section D: Servicing: Current Practices

401	How many times has your AC been serviced between April 2018 and May 2019 for:	
401-1	General maintenance? ____________________________	
401-2	Repairs and break-down maintenance? ____________________________________	

General maintenance is servicing that is undertaken to ensure good maintenance of the AC and lessens the likelihood of it failing. It is performed while the AC is still working so that it does not break-down unexpectedly.[3]

Break-down or repairs maintenance is carried out in response to a failed component or sub-optimal performance of the AC. Break-down maintenance is typically unplanned and is in response to issues faced during AC use.[4]

402	Why do/did you get general maintenance done for your AC?		
402-1	It was under warranty during the time of general maintenance		
402-2	Other reasons: please specify______________________________		
403	How important do you think regularly performing general maintenance of your AC is?	Very important ....1 Important ....2 Not important 3	
404	Do you have an extended service warrantee (ESW) for your AC?	Yes ....1 No..2	
405	If yes, why do you have an ESW on your AC? ____________________________		
406	Do you have an annual maintenance contract (AMC) for your AC?	Yes ....1 No 2	
407	If yes in D6, why do you have an AMC on your AC? ________________________		
408	Please rank the three most important sources of information you use to decide on a service technician for AC servicing:	Reference from Friend, neighbour, relative or co-worker........... 1 Online portals and websites (e.g. Urban clap) .... 2 Service technician recommended by retailer during purchase........ 3 Service technician sent bythe company 4 Prior self-experience with a technician 5 Others, (specify).................. 6	
409	How would you rate your awareness on AC servicing practices?	Well aware.............................. 1 Barely aware........................... 2 Not aware 3	
410	Indicate which of the following activities the service technician performed in the last servicing of your AC:		

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410-1	measure the current and voltage	Yes .... 1 No .... 2 Don't know............................... 99	
410-2	filter cleaning	Yes .... 1 No.. 2 Don't know 99	
410-3	leak testing with soap solution or with an electronic device	Yes .... 1 No.. 2 Don't know 99	
410-4	clean the inside of the AC	Yes .... 1 No.. 2 Don't know 99	
410-5	check for earthing	Yes .... 1 No.. 2 Don't know 99	
410-6	evacuation (a common process to remove non-condensable gases and moisture from refrigerants)	Yes .... 1 No.. 2 Don't know 99	
410-7	venting or release refrigerant gas from the AC unit	Yes .... 1 No.. 2 Don't know 99	
410-8	refilling or re-charging of refrigerant gas	Yes .... 1 No.. 2 Don't know 99	
410-9	recovery of refrigerant into a cylinder	Yes .... 1 No.. 2 Don't know 99	

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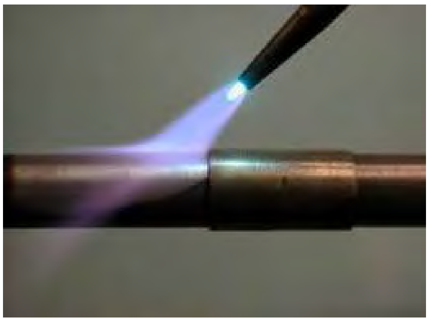
410-10	Brazing: a common method to seal the process tubes after charging is complete 	Yes .... 1 No... 2 Don't know 99	
410-11	Changing of filter drier 	Yes ....1 No...2 Don't know.............................99	
410-12	Tightening and capping of valves	Yes ....1 No...2 Don't know 99	
410-13	Do you think any of these servicing practices impact the environment?	Yes ....1 No...2	
If yes (1) to D11, please go to D12 **If no (0) to D11, please skip to D13.**			
410-14	Which one (please indicate) and how?	1) measure the current and voltage ______________ 2) filter cleaning ______________ 3) leak testing with soap solution or with an electronic	

		device______________ 4) clean the inside of the AC ______________ 5) check for earthing ______________ 6) evacuation______________ 7) venting or release refrigerant gas from the AC unit ______________ 8) refilling or re-charging of refrigerant gas ______________ 9) recovery of refrigerant into a cylinder ______________ 10) Brazing ______________ 11) changing of filter drier______________ 12) tightening and capping of valves ______________	
410-15	How much did you pay last time the service technician for general maintenance of your AC, when the refrigerant was not refilled? __________________________		
410-16	How much time did your AC's general servicing take the last time you had it done? ______________________		
410-17	Please indicate the extent of importance of the following attributes of an AC service technician:		

Attribute	1.Very important	2.Important	3.Not important
Price per service			
Knowledge of the technician			
Approachability of the technician			
Qualification of the technician			
Recommendation from a friend/ relative			
Prior experience with the technician			
Company they belong to			

		Others (please specify) ________					

Section E: Motivation for current servicing practices

501	Do you notice any change in your AC's performance after a general servicing?	Improvement in performance ……….1 Degradation in performance……….. 2 No change………………………….. 3 Don't know…………………………. 4	
502	How satisfied are you with the service technicians you last hired for general servicing?	Extremely Satisfied .... 1 Satisfied .... 2 Not Satisfied 3	
503	Does the service technician provide you with any information on the servicing practices undertaken during the servicing?	Yes .... 1 No 2	
504	What is your level of satisfaction with the quality of information provided to you by the service technician during servicing?	Extremely satisfied .... 1 Moderately satisfied............ 2 Neutral 3 Slightly satisfied .... 4 Not satisfied........................ 5	
505	Did you service technician advice you on good maintenance practices?	Yes .... 1 No 2	
506	What, according to you, are some of the good maintenance practices you follow while using your AC? ______________________________		

Section F: Perception on willingness to spend time and money on servicing

601	How much time would you be willing to spend on servicing each AC?	_______________	

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602	How much money would you be willing to spend on servicing each AC?	______________	
603	How would you rate the importance of regularly performing general servicing of your AC?	Very Important 1 Important 2 Not Important 3	

B: Consumer information (details of the respondent, continued)

B19	Please indicate your monthly household income: ___________________	
B19	How many ACs do you have at your house? For each AC in the household, please indicate:	

Details of AC		**codes**	**AC Unit.1**	**AC Unit.2**	**AC Unit 3**	**AC Unit 4**	**AC Unit 5**	**AC Unit 6**	**AC Unit 7**
Ownership	Rented	1							
	Self- Owned	2							
Where self owned, is it a second hand purchase?	Yes	1							
	No	2							
Year of purchase/rental	Less than one year ago	1							
	1-3 years ago	2							
	3-5 years ago	3							
	More than 5 years ago	4							
Make	Assembled	1							
	Branded	2							

Tonnage	Less than 1 tonne	1							
	1 tonne	2							
	1.5 tonne	3							
	2 tonne	4							
	More than 2 tonne	5							
Energy Star Labelling	No star labeling	0							
	1 star	1							
	2 star	2							

UNDERSTANDING THE RELATIONSHIP BETWEEN INDOOR ENVIRONMENT, ELECTRICITY USE AND HOUSEHOLD SOCIO-DEMOGRAPHICS: INSIGHTS FROM AN EMPIRICAL STUDY IN HYDERABAD

Gupta, Rajat[1], Tuteja, Sanjoli[1], Garg, Vishal[2], Agarwal, Rishika[2], Ramapragada, Pavan[2]

[1]*Low Carbon Building Research Group*
Oxford Brookes University
Oxford, United Kingdom
rgupta@brookes.ac.uk

[2]*Centre for IT in Building Science*
International Institute of Information Technology
Hyderabad, India
vishal@iiit.ac.in

ABSTRACT

Residential energy (electricity) use in India is expected to grow four-fold by 2030, yet there is paucity of empirical data that is essential for developing energy policy or programme. This study describes the methodology, findings and wider learning gathered from the concurrent monitoring of residential electricity use (current CT clamps) and indoor environment (temperature, relative humidity) every 15 minutes, along with household survey (occupancy, socio-demographics) of 20 dwellings located in the composite climate of Hyderabad. Statistical analysis of monitoring and survey data helps to better understand *what*, *when* and *why* electricity is used in dwellings with and without air-conditioning (AC). The 20 dwellings represent a variety of built forms (standalone houses/apartments), income groups (low/medium/high income) and ownership of AC units (from 0 to 4, average 1 AC). Mean annual electricity use of dwellings with AC units (2,881 kWh/year) was found to be 29% more than non-AC dwellings (2,230 kWh/year), while peak current consumption in AC homes was 228% more than non-AC homes. The coincidental monitoring of electricity current and indoor temperature confirmed the hours of AC usage, since indoor temperature decreased with rise of electricity current. This is why mean indoor temperature was higher (35ºC) and relative humidity lower (38%) in non-AC dwellings than dwellings with AC units (32ºC and 42%). The study also offers interesting lessons for future field studies in terms of *technology to technology interaction* (internet connectivity for data transmission), *technology to person interaction* (deploying loggers in appropriate location), and *person to person interaction* (sustaining householder engagement).

Keywords: **residential energy, monitoring, survey, indoor environment, electricity use**

INTRODUCTION

India is at the cusp of a major socio-economic development that suggest a four-fold increase in the country's carbon emissions by the year 2050 (du Can et al., 2019) Electricity consumption in residential buildings in India has nearly tripled since 2000 and today residential buildings account for about 24% of total electricity use in India (MOSPI, 2018). The annual average electricity consumption per electrified household for electrical appliances and lighting increased at a rate of about 3.7% per annum from the year 2000 to 2014 (WEC, 2014). This rising trend in India's residential energy consumption pattern is expected to further grow due to various factors such as the addition of nearly 20 billion square metres of new building footprint by the year 2030 (Kumar et al., 2010). Moreover the higher GDP growth is associated with increased purchasing power and higher comfort expectations, leading to higher penetration of household appliances, resulting in residential electricity consumption growth of about four-fold by 2030. Yet there is paucity of empirical data on residential energy use that is essential for developing energy policy or programme.

In 2013, a review of data quality related to building performance for residential and commercial buildings in four regions (India, China, United States and EU) found that building performance data for residential (and commercial buildings) sector was weakest in India. Moreover, the quality of data available for residential buildings in India was found to be weaker than commercial buildings. Lack of interest, technology and finance were identified as barriers to gathering residential energy data, which is why public availability of empirical data has been a long standing issue in India. Incentive programmes and regulations that promote continuous monitoring and reporting of building performance data were suggested as ways to overcome barriers (Shnapp and Laustsen, 2013).

With the emergence of smart meters providing an opportunity to collect granular time-series data on energy use of buildings, efforts are being made to make such data publicly available (Rashid et al., 2019, EDS, 2019). However, such initiatives are recent and still at a nascent stage. Furthermore, gathering data for residential buildings is particularly complex due to the heterogeneity of the building stock and lack of unified sources (Carpino et al., 2019). The unreliability of the electricity grid and internet also poses challenges for gathering data using remote monitoring (Batra et al., 2013)

Within this context, this study describes the methodology, findings and wider learnings gathered from the continuous and concurrent monitoring of residential electricity use (using current CT clamps) and indoor environment (temperature and relative humidity) every 15 minutes, along with a questionnaire survey of property (age, area) and household characteristics (occupancy, socio-demographics) of 20 dwellings located in the composite climate of Hyderabad. The study also draws lessons in terms of *person-person, technology-technology and person-technology interactions* when undertaking empirical studies for residential energy use in India. The study is part of a wider Indo-UK research programme called RESIDE – Residential Building Energy Demand Reduction.

METHODS

A socio-technical approach was adopted to gather in-depth qualitative and quantitative data about various social and technical aspects influencing electricity consumption of households in India. Building upon previous international (Gupta et al., 2014) and national studies (Rawal and Shukla, 2014, Sachar et al., 2018, BEE, 2014), a comprehensive monitoring and survey framework was developed, bringing together techniques of physical monitoring of electricity use and indoor environment, with a survey of property and household characteristics to explain *how much electricity is used* and *why it is being used.* These methods are explained below:

PHYSICAL MONITORING

Coincidental and continuous monitoring of dwelling electricity use (current CT clamps) and indoor environment (indoor temperature and RH) at every 15 minutes was performed using low-cost sensors developed and customised by the research team. Electric current measurements were used as a proxy to determine the trends in household electricity use. For this a low-cost battery operated CT logger- called GARUD (**Figure 1**), was developed, which consists of three CT clamps that can be installed on the main circuit board of a dwelling having one, two or three phase connection. The accuracy of Garud logger was tested in the lab and also in a dwelling (Tejaswani et al., 2019), by comparing Garud measurements with a more sophisticated logger that measures current, voltage and power factor. Yokogawa-WT330 meter was used for calibration of Garud. The data gathered using Garud was tested and calibrated against the WT330 meter. The device was calibrated on a wide range of current across the CT. Measurements were then compared to the true values over the range of current values. The comparison showed that Garud logger has an accuracy of +/- 3% to 5% (compared with standard meter with 60A/0.33V CT).

The logger for monitoring indoor temperature and RH logger called RHT BT (**Figure 1**) was customised by modifying an existing device to suit the requirements of the project. The accuracy of RHT BT was compared with that of i-button and Hobo U-12, and was found to be ± 0.3 deg.C for temperature and ± 3% for RH. Both devices recorded and stored data at every 15 minutes intervals. The data download process was simplified for Garud and RHT BT using Bluetooth. This allowed researchers to download the data on site using a customised app on their smart-phones, without removing and reinstalling any device.

One Garud and one RHT BT logger were installed in each of the 20 dwellings. While Garud was installed at the main circuit board by a trained electrician, the researcher installed the RHT BT in the most occupied room of the dwelling (with AC in case the dwellings had AC). Standard protocols (height from the floor, distance from external door/window or source heat and cold etc.) for installing an indoor temperature and RH logger were followed. The monitoring was conducted for a period of 14 days (15 May to 28 May), during the peak summer month of May 2019.

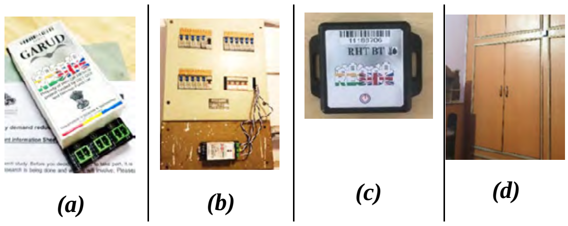

Figure 1: a) GARUD; b) GARUD installed on the main circuit board; c) T-zone; d) T-zone installed in a surveyed dwelling

SURVEY

The questionnaire survey was designed to gather data about the property characteristics as well as socio-demographic aspects of the households, covering the following aspects.

- *Built form* of the dwelling such as dwelling type (house, apartment), dwelling age, and floor area.
- *Building envelope* such as construction materials, architectural features such as shading.
- *Household characteristics* such as number of occupants, family size, socio-demographic (age, gender), income group.
- *Appliance* ownership, energy efficiency rating (BEE star rating) appliance usage hours.
- *Occupant thermal comfort* using thermal comfort sensation and preference votes.

The surveys were implemented using online Google forms, which the researchers completed on-site using their smart phones. Researchers read out the survey questions and noted participant responses on Google forms, which were recorded and saved online, thereby eliminating the effort for filling in the survey responses later on. The surveys were conducted through multiple visits wherein the researchers took photographs of the dwelling features (such as shading) and also noted their observations. At the end of each survey researchers were asked to fill a feedback form highlighting any issues faced while conducting the surveys and make any suggestions for improving the survey forms.

CASE STUDY DWELLINGS

A total of 20 dwellings (comprising 20 households) representing a variety of built forms, income groups and ownership of air-conditioning (AC) units were selected and recruited for the study. The availability of electricity data for the past one year (mid 2018 to 2019) was a key criterion for selecting the dwelling. Based on the annual household income data gathered from the residents the dwellings were categorised as low, medium and high income groups as defined under the Pradhan Mantari Awas Yojana. Nearly, 50% of the surveyed dwellings (9 out of 20) belong to the middle income group (MIG), while seven dwellings fell in low income group (LIG) and four in the high income group (HIG). The average number of occupants in the HIG, MIG and LIG households were found to be 3, 3.7 and 4.1 persons per household respectively. About a quarter of the dwellings (6 out of 20) did not have any AC units, while nearly half of the surveyed dwellings (9 out of 20) had one AC unit. The remaining five dwellings owned two, three and four AC units.

Though AC ownership was found to be highest in the high income group (HIG) (avg. 2.3 ACs/household) and lowest in LIG (avg. 0.6 AC/household), there were a few high income households with no ACs, as well as middle income households with 2 or 3 ACs. The number of occupants in a dwelling did not have any association with the number of ACs owned by the household (**Figure 2**). While majority of the dwellings without AC or with one AC had single phase electricity connection, dwellings with more than one AC also had three phase connection. There were a few dwellings with no AC units (n: 3) which had three phase connection.

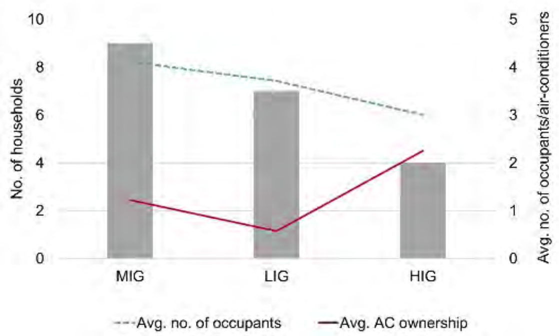

Figure 2: Income group distribution of the surveyed dwellings vs avg. number of occupants and ACs owned

Majority of the dwellings (13 out of 20) were stand-alone houses or bungalows with one electricity meter, seven dwellings were flats located in a low rise (< 4 story high) apartment building. Nearly all the surveyed dwellings were owner occupied, constructed using RCC frame structure with burnt clay bricks as infill. The windows were single glazed with fixed external shading. The average age of dwellings was about 10 years.

FINDINGS

Electricity consumption data for 20 dwellings were gathered for a period of one year (Aug 2018 to July 2019), through electricity bills from the householders or accessed online through the electricity supplier's website, with consent from the householder. **Figure 3** shows the annual electricity consumption of the six non-AC and 14 dwellings with AC units. A wide range in electricity use is observed, regardless of AC ownership. The overall mean and median annual electricity consumption for the 20 dwellings was found to be 2,686 kWh/year and 2,765 kWh/year respectively.

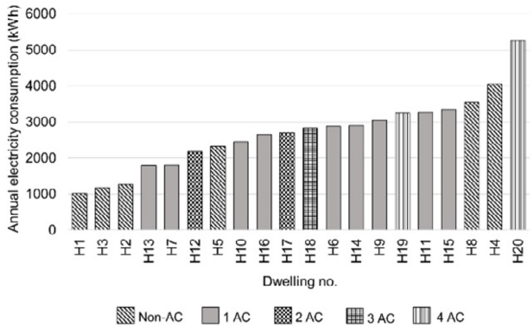

Figure 3: Annual electricity consumption of the surveyed households (August 2018 to July 2019)

Overall, the mean annual electricity consumption for AC dwellings was found to be about 29% higher than the non-AC dwellings. Understandably the mean annual electricity consumption was found to be lowest for non-AC dwellings (2,230 kWh/year) (n: 6) and highest for dwellings with four ACs (4,248 kWh/year) (n: 2) **(Figure 4)**. The difference between H20 (highest electricity user with AC) and H4 (highest electricity user without AC) is much less (1,210kWh), indicating that AC usage may not always be the most energy consuming end use and there are other factors influencing residential energy usage.

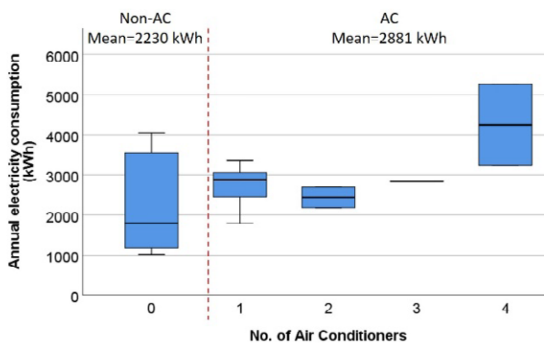

Figure 4: Box plot showing distribution of annual electricity consumption for non-AC and Ac dwellings

The mean daily electricity consumption for the 20 dwellings (based on 9 months data - Jan to Sept) was found to be 7.7 kWh. This daily electricity use is higher than the mean daily electricity consumption of 5 kWh (for Jan-Sep) measured by the NEEM study for Hyderabad by BEE and CLASP (EDS, 2019).

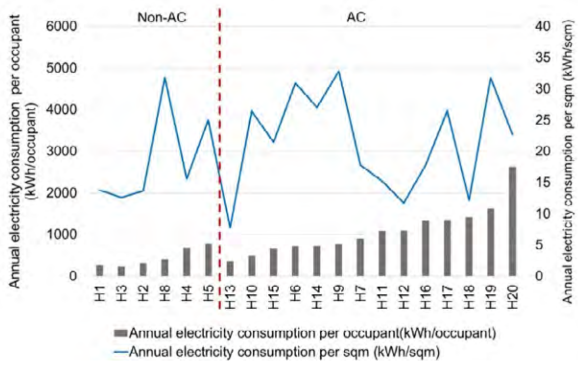

Figure 5: Annual electricity consumption per person vs per sqm electricity consumption of surveyed households

When electricity use was normalised by floor area and number of occupants, the annual electricity use of AC dwellings was found to be higher than non-AC dwellings (**Figure 5**). Within AC dwellings, the consumption varied significantly by conditioned floor area. Stronger correlation was observed between annual electricity use and electricity use per occupant (r: 0.67), as compared to moderate correlation (r: 0.44) between annual electricity consumption and electricity use per square metre. This implies that annual electricity use per occupant should be considered as a key metric, alongside annual electricity use per square meter (also called Energy Performance Index), especially in the Indian context where number of occupants can vary depending upon a nuclear or joint family structure. This is further reinforced by the weak correlation (coefficient value of 0.16) between annual electricity use per square meter and annual electricity use per person.

While mean monthly electricity consumption of non-AC dwellings was less affected by changes in external temperature, it had a major impact on electricity use of AC dwellings, with consumption being highest during summer months (May to June), and increasing with number of ACs and their usage (**Figure 6**).

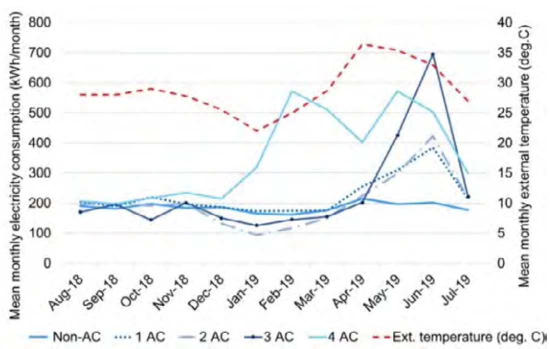

Figure 6: Mean monthly electricity use vs outdoor temperature

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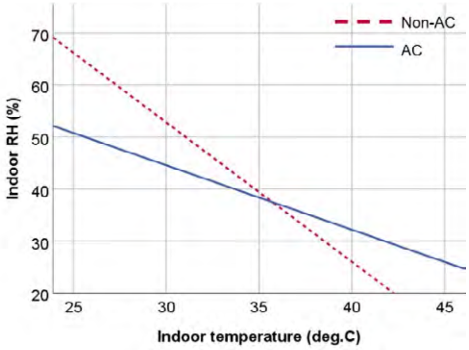
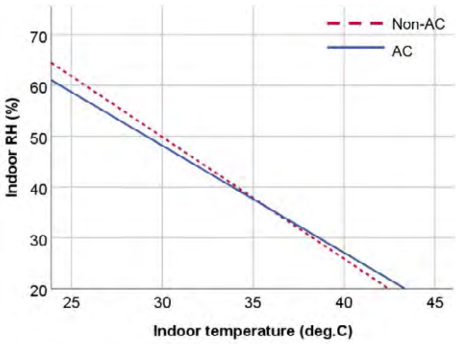
The mean indoor temperature (for the 14 day monitoring period in May 2019) for non-AC dwellings was found to be highest (35ºC) and similar to the mean outdoor temperature, whereas mean indoor RH was found to be lowest in these homes (38%). The mean indoor temperature for AC dwellings was lower (34ºC) but mean indoor RH (41%) was slightly higher than non-AC dwellings.

A scatter plot of indoor temperature and RH measurements during AC usage hours (9pm to 7am for 18 dwellings, and 9pm to 7am and 2pm to 7pm for two dwellings) for AC and non-AC dwellings (**Figure 7a**) showed that indoor relative humidity was maintained within a tight range (30% - 48%) in AC dwellings, as compared to non-AC dwellings (20%-75%). Interestingly during the period when AC was not used, dwellings with AC units behaved similar to dwellings with no ACs (**Figure 7b**), indicating the inability of the building envelope to retain coolth.



(a) during hours when AC is used



(b) during hours when AC is not used

Figure 7: Indoor temperature vs indoor RH (a) non AC; (b) AC dwellings

Within the group of dwellings with AC units, much wider variation was observed in the mean indoor temperature (**Figure 8**). While the mean as well as minimum indoor temperatures in dwellings with ACs are much lower than dwellings without ACs, given the wide range observed between minimum and maximum indoor temperatures in majority of the dwellings with ACs, it is evident that AC usage is not constant.

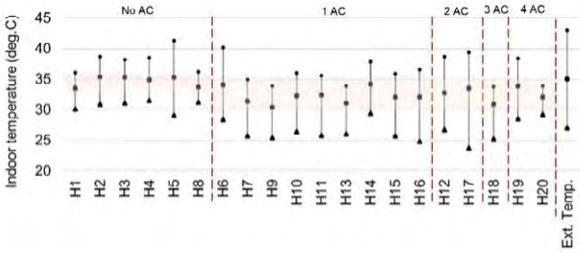


Figure 8: Mean indoor temperature of the surveyed dwellings vs mean external temperature

Since the temperature and RH logger was installed in the room with AC, the relationship between AC usage pattern and indoor temperature is examined further. **Figure 9** (a, b and c) shows the hourly average current and indoor temperature profiles over a 14 day period in May 2019, for dwellings with one, two, three and four ACs respectively. The peaks observed in the current profiles are likely to be due to AC usage given that as electricity current increases, indoor temperature decreases. The difference in mean indoor temperatures when AC was on (32ºC) and off (34 ºC) was found to be only 2ºC. The AC usage hours were estimated from the graphs to be from late evening to early morning hours, with some variation in the on/off time. However significant variation in the time and duration of AC usage was observed amongst dwellings with one AC unit indicating difference in occupant preferences. The preference to switch-on the AC seemed driven more due to the time of the day (when the occupants were home) rather than change in temperature. The hours estimated for AC usage from the electricity current profiles compared favourably with self-reported AC usage hours from the survey (**Table 1**), giving confidence in the estimate.

Interestingly the analysis of current profiles for dwellings with two AC units showed considerable differences in their AC usage. In dwelling H12, two ACs were used between 8pm and 5am (about 7 hours) and between 1pm and 4 pm (about 3 hours), while in dwelling H17 (with two AC units), only one AC was used during the monitoring period. This was validated by the survey data, wherein the occupants of H17 reported using one AC during summer (**Table 1**).

Similarly for dwellings H18, H19 and H20 having three and four AC units respectively, the current consumption for dwelling H19 from 9 pm to about 10 am is much lesser as compared to that of dwelling

H18 which has three AC units. Likewise, the current profile for H19 and H20 show that while majority AC units in these dwellings were being used during night time (sleeping hours), one AC was also used for a few hours during daytime. While the AC usage during daytime in H19 was similar to H20, the usage hours were less. These observations were validated by the number of AC usage hours reported in the survey. These findings indicate that dwellings with more number of ACs may not have higher electricity use than dwellings with lesser number, since the number of ACs that are actually used and their usage hours may vary significantly.

When electricity current consumption profiles of AC and non AC dwellings were compared, peak current consumption in AC homes is found to be 228 % more than non-AC homes. Furthermore the current consumption pattern of an AC and Non-AC dwelling during weekdays and weekends showed that there is increased consumption of current during weekends in the afternoon hours for both AC and non-AC dwellings. The consumption increased by 11.9% during weekends in the dwellings with AC whereas the increase was much less (1.7%) in non-AC homes.

DISCUSSION

This study has tested an interdisciplinary approach combining physical monitoring of electricity use and indoor environment with household surveys to better understand *what*, *when* and *why* electricity is used in a sample of dwellings with and without air-conditioning. Meaningful insights are drawn about the electricity use patterns and peak usage of residential air conditioning.

The metric of annual electricity consumption per occupant (kWh/occupant/year) was found to better explain the variability of electricity use across the 20 dwelling sample, than the conventional metric of annual electricity consumption per square meter (kWh/sqm/year). It is evident that annual electricity use normalised by number of occupants can be a useful metric in characterising the diversity of household electricity consumption across different climates and cultures of India.

The annual and peak electricity use of dwellings with AC units was found to be much higher than non-AC dwellings. However it was not the number of ACs, but the usage pattern of AC units that influenced the magnitude of electricity use amongst AC dwellings. The continuous monitoring of electricity current and indoor temperature confirmed the use of AC, since indoor temperature decreased with rise of electricity current. The time of AC use and the peak period of electricity coincided, and was found to be between 9pm and 7 am for the majority of AC dwellings. As the mains electricity grid in India gets decarbonised with introduction of more renewable energy (that is variable and intermittent), this residential peak period will need to be addressed through demand-side response and electricity storage.

Indoor relative humidity was found to be well-controlled during the time of AC usage, implying that air conditioning in dwellings is mainly used to modulate indoor humidity levels. However during the period when AC was not used, the indoor temperature and relative humidity in AC dwellings was found to be similar to non-AC dwellings.

In addition to insights gathered through the field study data, lessons were learnt through the process of undertaking the field study. Challenges were faced (and most of them overcome) while conducting monitoring and surveys, and these are organised through a combination of interactions; technology-technology, technology-person, and person-person (Darby and Liddell, 2015), as explained below.

Technology-technology interaction: While the Bluetooth functionality of the data loggers facilitated easy and quick data download, the mobile app required for downloading the data was found to be temperamental possibly due to connectivity issues. A limitation of the loggers was the non-availability of the option to pre-set the data logging date and time, with the result that not all dwellings started gathering data at the same time. However, this limitation can be overcome by installing the loggers for longer duration (say a year) such that substantial data for all seasons can be gathered. While conducting the survey, completing the forms online using smart phones was found to be an efficient method of gathering data, since it eliminated the process of filling in survey responses later. However connectivity issues were faced due to intermittent internet connection in some locations.

Technology-person interaction: Installation of data loggers in dwellings also posed challenges. Since the CT logger for monitoring electricity current had to be installed by an electrician at the main circuit board, it was vital to check beforehand that main circuit board was accessible and had enough space for installing the CT logger. Also the electrician had to ensure that no damage was caused due to the installation. To avoid any claims by the householders at a later stage, they were requested to sign a ‘no damage form’ following the installation. Photographic evidence of the installation was also gathered as part of the survey. The researchers were trained to carefully select the location while installing the temperature & RH logger.

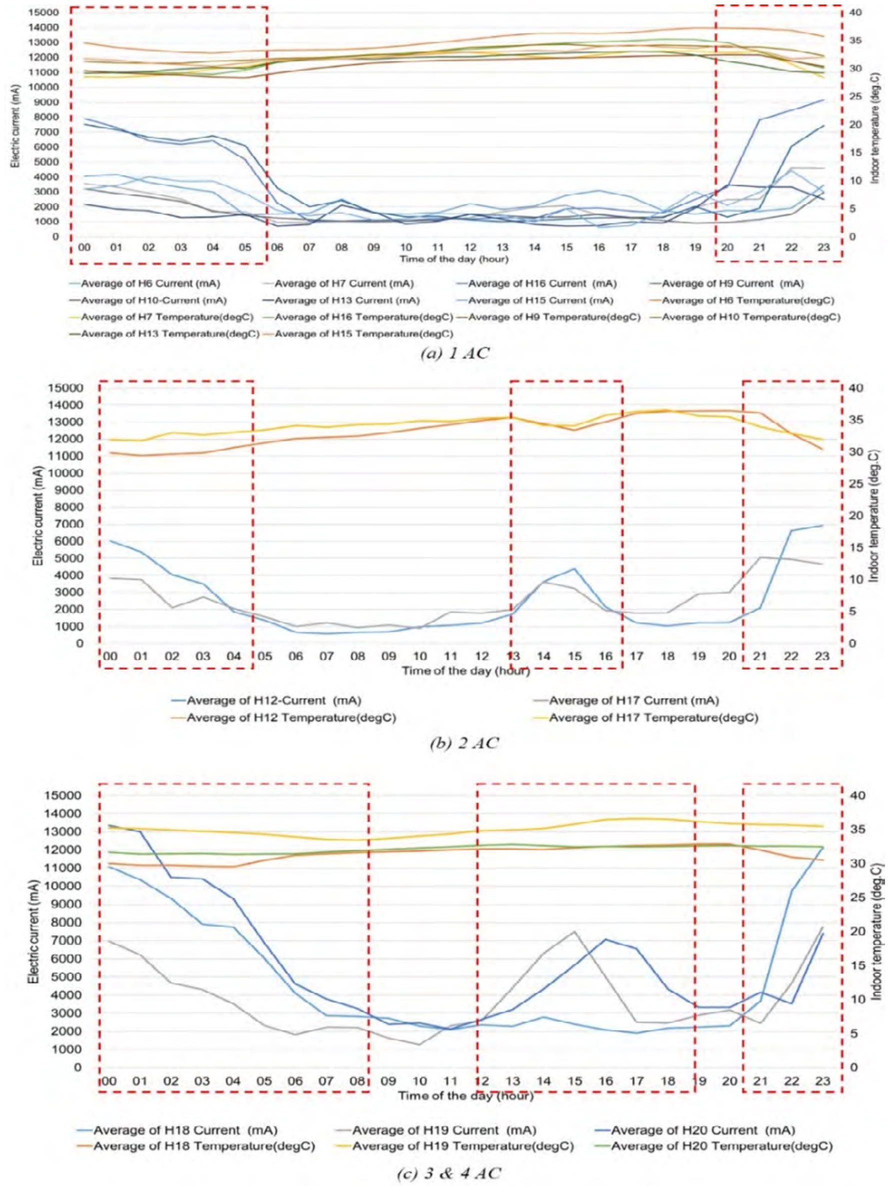


Figure 9: Hourly average daily electricity current and indoor temperature profile (based on 14 days data at every 15 minutes) for dwellings with a) 1 AC; b) 2 AC; c) 3 & 4 AC

Table 1: AC usage hours (per day during summer) reported by occupants & calculated from electric current profile

DWELL-ING NO.	NO. OF AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 1ST AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 2ND AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 3RD AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 4th AC	TOTAL CALCULATED AVG. USAGE HOURS/DAY (FROM ELECTRIC CURRENT PROFILE)
H6	1	5-8	-	-	-	7
H7	1	5-8	-	-	-	8
H16	1	9-12	-	-	-	11
H12	2	5-8	5-8	-	-	10
H17	2	9-12	Not used	-	-	11
H18	3	5-8	5-8	5-8	-	11
H19	4	5-8	1-4	1-4	Not used	10
H20	4	9-12	5-8	1-4	1-4	15

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For example, no loggers were installed in the vicinity of an AC, or near a window or balcony door, or near a source of direct cool air or heat. Again photographic evidence was gathered to confirm installation of RHT BT logger.

Person-person interaction: A key challenge was to get the householders interested in participating in such studies and making them aware about the significance and benefits of participation. During the study, although households were recruited through friends and family contacts, many householders lost interest and opted out of the study by the time the actual field study began. To address this in future, such studies must be mindful of the time lag between recruitment of dwellings and start of the field work. While some part of the survey (especially socio-demographics) could be self-completed by householders, in order to ensure complete set of responses, the surveys were undertaken in the form of interviews thereby increasing the duration of the survey. Providing some form of incentives (cash or in kind) to householders can help in sustaining their interest. The installation of the CT logger required an electrician accompanying the researcher, and on few occasions, householders requested the electrician to undertake additional electrical works. Since these works were not supported by the field study, researchers had to be trained to manage expectations of householders, without jeopardizing their participation in the study.

Such experiences from the field study provide useful lessons for conducting future empirical studies on residential energy in India.

CONCLUSION

This study has assessed the pattern of electricity use, AC usage and its relationship with indoor environment in a sample of 20 AC and non-AC dwellings in Hyderabad, using coincidental monitoring of electricity use (current monitoring using CT clamps) and indoor environment (temperature and RH) combined with household surveys. The learning from the process of undertaking the study offers useful insights for large-scale monitoring and survey based studies in India. While it can be argued that the advent and growing popularity of smart meters in India can eventually facilitate gathering of energy data, their penetration will be limited to certain socio-economic backgrounds and building typologies. The approach adopted in this project offers the means for gathering residential energy data on a nationwide scale.

ACKNOWLEDGEMENT

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THERMAL COMFORT IN AFFORDABLE HOUSING OF MUMBAI, INDIA

Jeetika Malik[1], Ronita Bardhan[2]

[1]*Centre for Urban Science and Engineering*
Indian Institute of Technology Bombay
Mumbai, India
jeetika.malik@iitb.ac.in

[2] *Department of Architecture*
University of Cambridge
Cambridge, UK
rb867@cam.ac.uk

ABSTRACT

Indian affordable housing sector, with a projected demand of 38 million units by 2030, offers an immense opportunity to explore thermal comfort preferences and reduce building energy consumption. This work aims at understanding thermal comfort preferences and adaptive occupant behaviour within the affordable housing located in hot and humid climate. The study presents the results from a longitudinal field survey conducted in free-running affordable housing of Mumbai, India. A total of 705 set of thermal comfort observations were recorded across three different periods from August 2018 till May 2019. The findings reveal that occupant comfort existed in a wide range of temperatures from 19.8°C to 34.8°C across the three seasons with a mean comfort temperature of 28.36°C. Further, the results suggested that there is a greater influence of outdoor climate on the thermal adaptation of affordable housing residents than that suggested by the exisiting thermal comfort standards. Thus, it is imperative to review the existing codes and standards to ascertain their applicability in the affordable housing segment. This study would help in advancing thermal comfort standards and guidelines for Indian context thereby reducing building energy consumption. Further, it also provides an insight to the thermal comfort conditions within the subject housing which could aid in the design of future affordable housing stock.

Keywords—thermal comfort, comfort standards, adaptation, affordable housing

INTRODUCTION

The Ministry of Environment, Forest and Climate Change recently launched the India Cooling Action Plan (ICAP) focusing on reduction of India's cooling loads to achieve the country's plan for climate change. One of the goals of this ambitious proposal is to provide sustainable cooling and thermal comfort for all through the adoption of adaptive thermal comfort standards (Ministry of Environment Forest & Climate Change, 2019). So far energy efficiency policies have focussed on improving building technologies, however, ICAP in its pioneering attempt aims at developing adaptive thermal comfort standards for buildings to reduce energy guzzling (Somvanshi, 2019). National Building Code (NBC) of India prescribes the indoor comfort temperature based on the India Model for Adaptive Comfort (IMAC) which is limited to the field studies in office buildings. Moreover, IMAC disregards the climatic variations and proposes a standard comfort range across the country. There is thus an exigency to establish adaptive thermal comfort standards suitable to different building typologies and climatic regions.

India has been witnessing numerous developmental challenges due to the rapid urbanization and rural-urban migration. Urban housing shortage, particularly in the affordable housing segment, is one such challenge that needs to be addressed effectively. Government of India (GoI) has undertaken multiple efforts in the past years to tackle the urban housing shortage through policies and schemes such as National Housing Policy, 1994; Jawaharlal Nehru National Urban Renewal Mission, 2005; Rajiv Awas Yojana 2013 (Reserve Bank of India, 2018).The most recent scheme launched in 2015, Pradhan Mantri Awas Yojana (PMAY), which subsumes all the previous urban housing schemes, aims at providing affordable 'Housing for All' by the year 2022 (KPMG, 2012; Ministry of Housing & Urban Poverty Alleviation Government of India, 2015). According to the 2017 technical report by the Ministry of

Housing and Urban Poverty Alleviation (MoHUPA), there is an estimated urban housing shortage of more than 18.78 million homes at the beginning of 2012, of which 96% were in the EWS (Economically Weaker Sections) and LIG (Low Income Group) segments (Ministry of Housing & Urban Poverty Alleviation Government of India, 2012). Furthermore, the demand for affordable housing is expected to increase to 38 million units by 2030 (McKinsey, 2010). Against this massive housing deficit, the urban component of PMAY had initially proposed construction of 20 million units by 2022 which has been revised to 12 million (MoHUA, 2017). Given the magnitude of affordable housing to be built in India and its potential in improving energy efficiency, there exists an immense opportunity to explore thermal comfort preferences in such housings and improve occupant comfort, health and well-being.

This study focusses on analysing thermal comfort conditions within the naturally ventilated affordable housing of Mumbai, India. The aim is to comprehend the occupant preferences for thermal comfort and pave way for the development of better thermal comfort standards. The major objectives of this study are:

- To investigate thermal enviornment within the affordable housing
- To determine the thermal comfort ranges and neutral temperature
- To investigate the applicability of existing comfort standards to affordable housing

STUDY AREA

Mumbai is India's most-populous city, and it is one of the largest and most densely populated urban areas in the world. The city has been unable to cope with the rapid increase in its population, resulting in around 41.9 % of the population, i.e. 5.2 million living in slums (Census 2011), for want of affordable housing. Moreover, with the Indian middle class expanding, Mumbai is forecasted to register the highest cumulative residential demand growth of 23% in the affordable housing segment (India Brand Equity Foundation, 2010). In addition, policy initiatives by Government of India towards affordable housing particularly, "Housing for all by 2022"(Ministry of Housing & Urban Poverty Alleviation Government of India, 2015) and the successful "Slum Rehabilitation Scheme" (Nijman, 2008) aids the growth of affordable housing stock in the city. Hence, the city of Mumbai serves as an exemplary case for carrying out this study.

Mumbai, being on the seacoast, experiences a tropical savanna climate (Koppen classification) with a heavy southwest monsoon rainfall. Mumbai falls within the "*warm and humid*" climate zone as per the National Building Code of India. Cool weather prevails from December to February and hot weather from March to May. The rainy season, with high relative humidity and gusty winds, lasts from June to September and is followed by the post-monsoon season, lasting through October and November, when the weather is again hot. The average annual temperature is 27.2 °C and the average annual precipitation is 245.7 centimeters (M.C.G.M., 2011).

RESEARCH METHODS

Thermal comfort field studies were carried out in nine affordable housing buildings situated in two localities of Mumbai, India to understand the thermal comfort conditions and preferences of the occupants. Two distinct neighbourhoods were selected to understand the locational differences in the thermal preferences, if any. Of the nine buildings surveyed, three were the slum rehabilitation buildings (SR1, SR2, SR3) located in Govandi (L1), Ward-M of Mumbai. These buildings were G+7 hyper dense structures with an inter building distance of 3 meters. Each building consisted of 84 single room units with an integrated cooking area and an attached toilet having a total floor area of about 23 square meters (see Figure 1c). The other six buildings (IC1 to IC6) were located in the residential campus of Indian Institute of Technology Bombay located in Powai (L2), S-ward of Mumbai. IC1 and IC2 were G+2 structures comprising of 12 one-room tenement units having an area of 28 square meters each with kitchen, balcony and washing area. These buildings had common toilet facilities on each floor as depicted in Figure 1b. IC3 to IC6 were also G+2 structures with two room units with kitchen, balcony and an attached toilet having an area of 35 square meters each. IC1 to IC6 were located in the lush green campus of IIT Bombay having inter building distances of more than 6 meters. All the surveyed buildings were operated in free running mode at the time of survey with operable windows and doors. The buildings were built with conventional brick and-mortar wall and reinforced cement concrete (RCC) frame structure. IC1 and IC2 had RCC pitched roofs

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as depicted in Figure 1a, while the rest of the buildings had RCC flat roof.

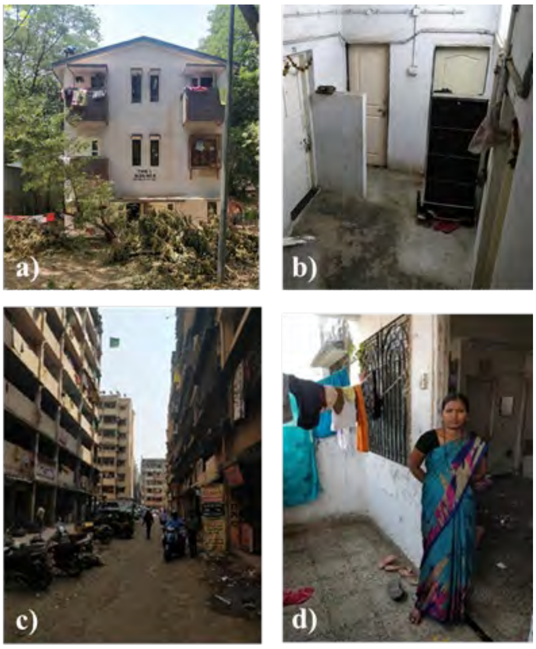

Figure 1: Glimpses from the field study

Data Collection: Longitudinal Field Survey

Longitudinal survey method, conforming to class II protocol, was adopted to gather subjective comfort responses of the subjects and simultaneously measure the immediate thermal surroundings in the affordable housing of Mumbai, India. The field surveys were administered in three different phases from August 2018 till May 2019 to capture the seasonal variation of thermal comfort. The survey was conducted thrice a day from 9:00 a.m. to 9:00 p.m – morning (9:00 a.m to 12:00 noon), afternoon (12:00 noon to 5:00 p.m.) and evening (5:00 p.m. to 9:00 p.m) such that no consecutive readings were taken before 2 hours. The subjects voluntarily willing to participate in the survey were briefed about the details and its purpose. Subjects residing within the environment for less than 6 months were excluded since they might not have been familiar of the thermal environment and the use of environmental controls. The number of subjects varied in each phase as some of them were either unavailable or were unwilling to participate. From 19th August 2018 till 19th May 2019, 20 days (two days in August, four in September, and seven each in January and May) were invested for carrying out the surveys. To avoid any selection bias, an effort was made to randomly stratify the samples based on floor location, gender, age and time of the day.

Questionnaire and scale used

The questionnaire was prepared in English and then translated into Hindi, the locally spoken language in Mumbai. The questionnaire had four parts: personal identifiers, subjective thermal responses and preferences, personal variables and behavioural adaptation. The questionnaire was filled thrice a day for each subject. ASHRAE's seven-point scale of thermal sensation (TS), Nicol's five-point scale of preference (TP) and four-point scale of skin moisture (SM) were used in this study.

Measurement of outdoor and indoor variables

The meteorological data for outdoor temperature (Tout) and relative humidity (Rh) was obtained from wunderground online for each of the survey days. The recording station was 14 kms and 1 km from the surveyed buildings in L1, Govandi from L2, IIT Campus respectively. Testo 480 meter along with a set of probes as described in Table 1 were used for measuring the indoor environmental variables: indoor air temperature (Ta), globe temperature (Tg), relative humidity (RH), air velocity (Va), carbon di-oxide concentration (CO2), and the lighting level (L). The instruments were assembled and placed on a tripod at a measuring height equal to the working plane of the subjects as illustrated in Figure 2. The assembly was placed close to the subjects and at least 0.60 meters away from the external walls and electrical equipment.

Table 1: Details of the instruments used for the environmental measurements

Instrument	Parameter measured	Range
Testo 480 IAQ probe	Air Temperature	0 to +50 °C
	Relative Humidity	0 to 100 %RH
	Ambient Carbon dioxide	0 to +10000 ppm
Globe thermometer (150mm)	Globe Temperature	0 to + 120 °C
Vane probe (Ø 100 mm)	Air velocity	+0.1 to +15 m/s
Testo 480 lux probe	Lux level	0 to +100000 Lux

Figure 2: Instrument Setup

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Measurement of personal and environment controls

The metabolic activity and clothing, were recorded in all the surveys in the field data sheet against each participant. Metabolic rates were estimated for the activities filled in data sheet, in accordance with the ISO 8996 "Ergonomic of the thermal environment—Determination of metabolic rate" (International Organization for Standardization, 2004) The clothing worn by the respondents was recorded at the time of survey and the corresponding clothing insulation, Clo values were calculated based on the lists published in ASHRAE Standard 55-2010 (Standard-55, 2017). The clothing garment checklist was revised to add Indian garments for women and men, such as sari, kurta, pajama, etc according to the studies conducted in Indian context (Havenith et al., 2015; Indraganti, Lee, Zhang, & Arens, 2015; Rawal, Manu, Shukla, Thomas, & de Dear, 2016). The estimation of clo values took into account the chair insulation as well.

RESULTS

Sample size distribution

A total of 705 responses were obtained from the three phases of field surveys. About 76% of the responses were obtained from the females while 24% were from the male respondents (Fig 3a). The seasonal distribution of survey responses, as presented in Fig 3b, comprised of 39.3% in monsoon season followed by 35.9% and 24.8% in winters and summers respectively. Location 2 (IIT Campus) housing has a slightly higher share of responses in the monsoon season and winter season (Fig 3c). Almost equal number of responses were obtained for the summer season from each of the neighborhood locations. The surveys were spread across three time of the day- morning, afternoon and evening. A majority of the responses were collected during afternoon (40.9%) and evening hours (42.1%) while about 17% were obtained from the morning hours.

Figure 3: Descriptive of the survey

Subjective thermal responses

44.7% of the votes on the thermal sensation scale were recorded for neutral (0), while another 24.4% and 21.0% of the votes correseponded to slightly cool (-1) and slighty warm (+1) sensation. The mean thermal sensation vote, TSV across the combined data (n=705) was found to be 0.11 which is slightly higher above the neutral (0). The correlation between the subjective thermal votes, TSV and TPV (thermal prefernce vote) suggested high positive and significant association (r = 0.708, N = 705, p < 0.001). About 17% of the samples voting neutral on the TSV scale preferred a cooler environment while another 1% preferred a warmer environment. Figure 4 illustrates the relationship between TSV and TPV votes across the samples. The graph shows that warmer and cooler preference votes intersect slightly towards the cooler side of thermal sensation scale indicating a slightly cooler than neutral preference among the subjects. This was possibly because of the thermal history of the subjects as the natural desire of most people living in a hot climate to prefer a cooler condition, although they probably accepted the prevailing conditions (Damiati, Zaki, Rijal, & Wonorahardjo, 2016). Similar observations have been made by Rijal et al.(Rijal, Yoshida, & Umemiya, 2010), Damiati el al.(Damiati et al., 2016) and Indraganti & Boussaa (Indraganti & Boussaa, 2017) for hot/warm and humid climate zones.

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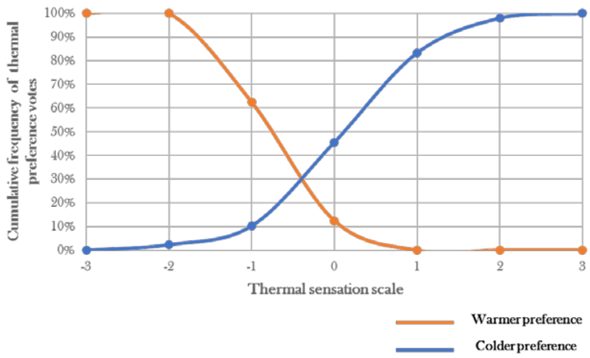

Figure 4: Relationship between TSV and TPV

Fig. 5 shows the relationship between thermal sensation votes (TSV) and the outdoor air temperature. Here, the daily mean outdoor air temperature (T_{dm}) has been adopted as it had the highest coefficient of determination (R^2=0.29) as compared to prevailing monthly mean and daily running mean outdoor air temperature. As suggested by Hooi, Toe, & Kubota (Toe & Kubota, 2013), the possible explanation of choosing T_{dm} is the dependence on previous days' acclimatization in the hot–humid climate is less likely owing to the small changes in daily outdoor weather conditions over the entire year. The relationship reveals a significant association between T_{dm} and TSV (N = 705, $p < 0.001$, r=0.54, R^2=0.29). The occupants voted neutral for a wide range of outdoor temperatures indicating thermal adaptation among the survey population.

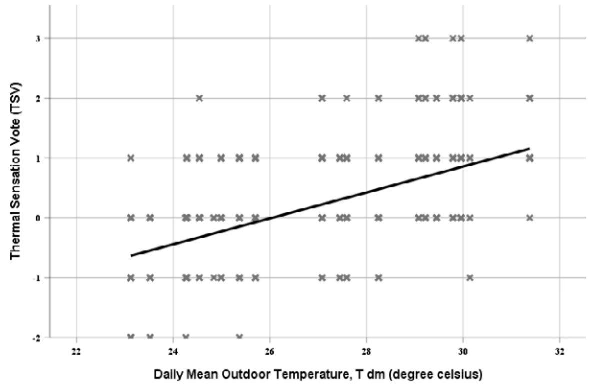

Figure 5: Relationship between thermal sensation votes and outdoor temperature

Comfort temperature

The thermal responses of subjects in the form of acceptable temperature range, neutral temperature, and thermal sensitivity can be deduced from a linear regression model of ASHRAE scale votes against indoor air temperature (Humphreys, Nicol, & Roaf, 2016). Comfort temperature (T_{comf}) is estimated by regressing thermal sensation vote (TSV) over indoor temperature (Humphreys et al., 2016). This study adopts indoor operative temperature (T_{op}) over globe temeperature and air temperature for analysis of comfort conditions because T_{op} considers the radiation and air velocities and hence could explain the thermal environment better.

The regression results yielded a significant but moderate relationship (N = 705, $p < 0.001$, r = 0.562, R^2 = 0.316) between TSV and T_{op} as provided in Table 2. A low coefficient of determination, R^2 value of 0.32 suggests the individual variations in subjective responses. T_{comf} was calculated from the resultant equation at TSV=0 and was found to be 28.36 °C. The comfort temeprature band, corresponding to TS vote from -1 to +1, was found between 24.55 °C to 32.16. A wide comfort band suggests that occupants of affordable housing either adapt to a range of temperature through adaptation measures or are more forgiving towards their thermal environment.

Table 2: Linear regression results

No. of Obs.	Regression equation	R^2	r	T_{comf}
705	TSV = $0.26T_{op}$ -7.46	0.32	0.56	28.36

The slope of the resultant equation indicates about the sensitivity of the population to changes in the indoor temperature. A slope of 0.26 °C^{-1} when compared with the findings by Indraganti et. al (Indraganti, Ooka, Rijal, & Brager, 2014) and Rajasekar & Ramachandraiah (Rajasekar & Ramachandraiah, 2010) suggested that the surveyed population is less sensitive to temperature changes. Occupants of affordable housing, in absence of space-conditioning equipment due to economic constraint, may have relied majorly on the available adaptive opportunity for restoring comfort and thus are more tolerant to increased temperatures. Similar inferences were made by Indraganti and Rao (Kubota, Bahadur, & Hiroto, 2018) while analysing the effect of economic group on thermal comfort for Indian residences.

Literature suggests that the presence of adapatation may depress the regression coefficient leading to misleading values of comfort temperature (Rijal et al., 2010). Moreover, the deviation in TSV away from the neutrality, may also adversely affect the predictive power of the resulting regression equation (Indraganti et al., 2014). To solve these problems, Griffiths' method (Griffiths & Boyoe, 1971)was adopted to calculate comfort temperature. According to this method, the Griffith's neutral temperature, T_{ng} is given by:

$$T_{ng}= T_{op} +(0\text{-}TSV)/G \qquad (6.2)$$

Where G denotes the Griffiths' constant representing a change in the Griffiths' neutral temperature per unit change in comfort votes. In applying the Griffiths method, Humphreys et al. (Humphreys, Nicol, & Raja, 2007) and Rijal et al. (Rijal et al., 2010) adopted the constants 0.25, 0.33 and 0.50 for a seven-point thermal sensation vote. In this study, a regression coefficient of 0.26 has been observed. Griffith's neutral temperature, T_{ng} was calculated for each of these values (0.25, 0.33, 0.50 and 0.26) and there were no stark variations in the mean T_{ng}. Thus, G=0.26 was chosen for further analysis. Griffith's method yielded a mean T_{ng} of 28.39 °C which is close to the temperature, T_{comf} of 28.36 °C obtained from regression analysis. T_{ng} also showed close agreement with the operative temperatures when voting neutral. A standard deviation of 2.94 could be attributed to the effects of adaptive actions among the subjects. The mean T_{ng} estimated here is close to that reported in Indian studies conducted by Indraganti 2010 (Indraganti, 2010) and Rajasekar & Ramachandraiah 2010 (Rajasekar & Ramachandraiah, 2010) for same climatic zone. No significant differences in the mean neutral temperature (T_{ng}) and comfort ranges were found among the two locations. Although there were striking differences in the thermal adaptation measures among the residents of two locations, but it is not within the scope of this paper.

The operative temperatures corresponding to neutrality were then plotted against the daily mean running outdoor temperature and superimposed on the adaptive model for hot-humid developed by Hooi, Toe, & Kubota, 2013 (see Fig 6). This model was based on ASHRAE RP-884 database and was applicable to naturally ventilated buildings and thus seemed appropriate for comparison. The graph suggests that Hooi, Toe, & Kubota's model constantly predicts a lower neutral temperature for the subject dwellings with more than half of the data lying above the upper limit. Moreover, the regression coefficent (0.57) was found to be slightly lower than the existing study (0.62). This implies that the occupants of affordable housing were more adaptive than the global population. A detailed analysis of the thermal adaptation involving behavioural and physiological factors within the affordable housing would be helpful in establishing these relationships.

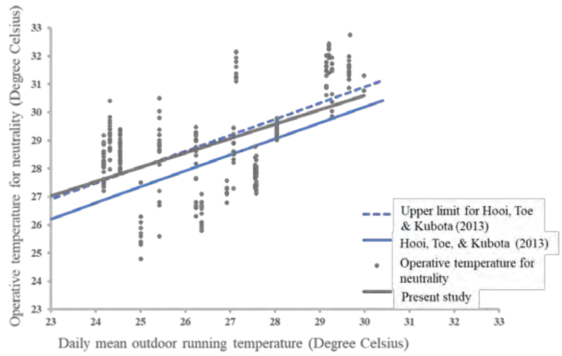

Figure 6: Comparison with Hooi, Toe, & Kubota's model

Comparison with existing standards

Thermal comfort standards determine the building energy consumption and are therefore crucial in building sustainability (Djongyang, Tchinda Rene´, & Njomo, 2010). A comparative assessment was done to ascertain the suitability of thermal comfort standards in predicting comfort conditions for the subject dwellings. Neutral temperatures calculated from the ASHRAE's adaptive thermal comfort model (Standard-55, 2017) and National Building Code IMAC model (Bureau of Indian Standards, 2016) were compared with those dervied from this study.

Table 3: Comparison summary of neutral temperature obtained from Griffith's method and existing comfort models

T_{ng}	Mean	S.D.	Min	Max
Present Study	28.39	2.94	19.80	34.70
IMAC (NBC 2016)	27.25	1.26	25.9	29.26
Adaptive model (ASHRAE 55-2010)	26.08	0.72	25.3	27.23

Table 3 presents the comparison summary and suggests that both the standards predicted a lower mean neutral temperature for the affordable housing Additionally, both the international standard, ASHRAE and the national standard, NBC predicted a narrow comfort range (2-3.26 °C). To get a deeper insight, neutral operative temperatures from this study were superimposed on the ASHRAE and IMAC models as illustrated in Figure 7. The graph witnesses that much of the observed neutral temperatures fall on the warmer side above the limits of thermal comfort standards. Though both the standards are ineffective in predicting the neutral temperatures for the affordable housing of Mumbai, IMAC model performs better than the ASHRAE model. The possible reason for this trend could be that ASHRAE database is representative of diverse building typolgies and regions across the world where the occupants may have different thermal comfort sensitivities and preferences to thermal adaptation.

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Moreover, IMAC model, which is based on the field surveys within Indian office buildings, considers the thermal preferences and adaptation of employees across all the climatic zones. The representative population for IMAC might have a difference in the availability of adaptive opportunites, socio-economic constraints and contextual settings than the affordable housing residents, leading to significant differences in thermal comfort preferences.

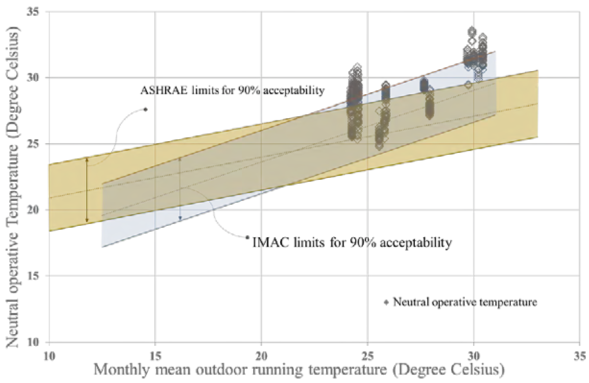

Figure 7:Comparison with ASHRAE and IMAC models

It is evident that there is a greater influence of outdoor climate on the thermal adaptation of affordable housing residents than that suggested by the exisiting thermal comfort standards. This points towards the development of a localised thermal comfort model which could account for the socio-cultural, economic and contextual factors.

DISCUSSION

The results for this study reveal that affordable housing residents of Mumbai have a wider comfort range than that predicted by the existing standards attributed to the presence of high thermal adaptation measures. This incorrect estimation of thermal comfort limits often contributes to building performance gap in the existing buildings. Though at present-day, the affordable housing residents do not rely much on energy-intensive measures for thermal comfort however, the probable rebound effects in future may lead to higher energy consumption for cooling needs (IPCC, 2014). Thus, it is timely to develop robust thermal comfort standards to reduce bulding energy consumption and improve upon occupants health, well-being and productivity. The first and foremost step towards sustainable thermal comfort standards shall be the contemplation of non-thermal factors such as income, lifestyle, socio-cultural regimes and the contextual settings. Previous studies in context of Mumbai and Hyderabad suggest that triggers for adaptive actions such as opening of windows or doors, use of exhaust fans etc. may not be limited to thermal discomfort (Indraganti, 2011; Lueker, Bardhan, Sarkar, & Norford, 2019). The prevailing socio-cultural regimes, economic constraints and contextual factors often affect the adoption of adaptive actions among the residents (Malik & Bardhan, 2019). Thus, it is imperative to review the existing codes and standards to ascertain their applicability in the affordable housing segment.

A better thermal comfort model would also help in informing the policy makers and designers on designing the future affordable housing. With 12 million affordable housing units yet to be built under the "Housing for all" scheme by 2022, improving upon the thermal comfort standards could lead to significant reduction in building energy thereby aiding in the country's climate change action plan.

CONCLUSION

This study presented the findings from a longutidinal thermal comfort survey conducted in the affordable housing of Mumbai, India to examine the comfort comfort conditions and energy implications. The results revealed that about 45% of the times occupants voted "neutral" on thermal sensation scale indicating satisfaction within the thermal enviornment. Mean thermal sensation vote, TSV was found to be 0.11 which is slightly higher above the neutral (0). Further, occupant comfort existed in wide range of temperatures from 19.8°C to 34.8°C across the three seasons with a mean comfort temperature of 28.36°C. The results also indicated the presence of high thermal adapatation among the subjects, which may be attributed to economic constraints. The existing comfort standards, when compared with the results from this study, proved to be ineffective in predicting comfort conditions for Mumbai's affordable housing. It was observed that the subjects were less sensitive to higher indoor temperatures, due to adoption of adaptive actions, than suggested by ASHRAE and IMAC models.

Indoor thermal comfort plays a significant role in determining building energy but is often neglected in policies and regulations for energy efficiency. This study provides an insight to the thermal comfort condiitons within the subject housing which could aid in the design of future affordable housing stock. Further, it could also help in reducing building performance gap thereby leading to energy efficiency. The future work would be to understand the occupant's behavioural responses to thermal adaptation and their intergation into thermal comfort models.

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UNDERSTANDING ELECTRICITY CONSUMPTION AND APPLIANCE OWNERSHIP IN TWO CITIES SOUTH INDIA

Santhosh Cibi[1], Ravichandran K[2], Sumathy Krishnan[3], Sumedha Malaviya[4], Kiran B[5]

[1]*Energy & Environment, Technology Informatics Design Endeavour (TIDE) India*
Technology Informatics Design Endeavour (TIDE) India
Bangalore, India
santhosh.cibi@tide-india.org

[2]*Energy & Environment, Technology Informatics Design Endeavour (TIDE) India*
Technology Informatics Design Endeavour (TIDE) India
Bangalore, India
ravi.k@tide-india.org

[3]*Energy & Environment, Technology Informatics Design Endeavour (TIDE) India*
Technology Informatics Design Endeavour (TIDE) India
Bangalore, India
k.sumathy@tide-india.org

[4]*Energy Program, World Resources Institute India,*
World Resources Institute India
Bangalore, India
sumedha.malaviya@wri.org

[5]*Energy & Environment, Technology Informatics Design Endeavour (TIDE) India*
Technology Informatics Design Endeavour (TIDE) India
Bangalore, India
kiran.b@tide-india.org

ABSTRACT

Residential electricity consumption in India has grown rapidly since 2000. With growing population and rapid urbanization, many studies have projected five to six times increase in consumption by 2030 under business-as-usual scenario. Electricity sector alone accounts for about 40% of India's total GHG emission, predominantly CO_2. Government has initiated various policy measures and schemes for promoting demand side management and efficient appliances. However, establishing ground level baseline and acquiring data-based evidence to validate these interventions is a challenge, particularly considering the very low penetration of smart meters. To complicate things, human behaviour aspects influencing decision on purchase of efficient appliances or generally determining conservation attitude is not easy to capture. VidyutRakshaka program was conceptualized to address some of these gaps and to provide field-based evidence.

Based on household electricity data from two cities, obtained through consumer-focused residential electricity conservation program VidyutRakshaka (VR), this paper will cover: (1) Presenting trends in consumption patterns within the city and across cities of Bangalore and Chennai and (2) Correlation of electrical appliance ownership with consumption disaggregated by size of the house. We believe that this analysis using ground-level data will benefit researchers and policy makers. It also provides inputs for strategizing interventions to meet our national goals on climate change and low carbon future.

Keywords—VidyutRakshaka, Home energy reports, Demand side management, Electrical appliance holding, household size based disaggregated data on electricity consumption

INTRODUCTION

VidyutRakshaka (VR) is a consumer-focused electricity conservation program, providing customised home electricity reports to participating households. The vision of the program is conserving electricity through awareness, nudges for long-term behaviour change, and information for better choice in electrical appliances.

The objectives of the program are:

1. Facilitate sustainable residential electricity consumption template for all categories of households through awareness and information

2. Demonstrate low carbon pathway to demand side management, in a resource efficient manner

3. Gain ground level, demographically disaggregated insights on residential electricity consumption

VR continues to be operational in Bangalore since 2015 and was piloted in Chennai in 2018. Participation is voluntary and free of cost. A generic awareness booklet is given on signing up for the program and then consumers receive customized home electricity reports at a certain frequency.

While home electricity reports constitute a critical component of the program, data obtained from consumers through the questionnaires provide valuable insights into residential consumption trends and electrical appliances. This paper is based on the study looking at the correlation of consumption with data on appliance ownership obtained from consumers in Bangalore and Chennai. The findings from the study would be useful in the context of increased emphasis on end user efficiency driven by electricity suppliers as recommended by the Intergovernmental Panel on Climate Change (IPCC) in their 5th Assessment report [Lucon, O et.al, 2014]

BACKGROUND

In cities, 70% of daily energy needs are electricity based and around 78 % of this comes from electricity generated from fossil fuel-based sources [Central Electrical Authority, 2014]. Residential (domestic) sector is the second largest consumer of electricity in India accounting for 24.2% [MOSPI, 2019] of total consumption. Our national Grid contributes 0.8 tCO_2\MWh to GHG emissions every year [Central electrical Authority, 2014]. In developing countries like India, residential buildings consume directly and indirectly 24.4 PWh every year [IEA, 2010]. These statistics give a sense of contribution of residential electricity consumption to GHG emissions.

Residential electricity consumption (REC)

Residential electricity consumption (REC) has grown by over 50 times from 1971 [Prayas (Energy) group, 2016]. Increasing urbanisation, effects of climate change resulting in extreme events and increasing economic prosperity, shifts focus of energy conservation on urban households using multiple high energy consuming appliances.

Role of electrical appliances in REC

To understand the effects of appliance ownership in REC in NCR region, a study published by Prayas Energy group in 2017 highlights the ubiquitous penetration of fans, TVs and fridges across households. With increasing income levels and rising ambient temperatures, penetration of ACs in Indian households is predicted to increase by two folds [Radhika Khosla, 2017]. In a study conducted in Pune, looking at data collected through metering of individual appliances, it was found that old refrigerators (more than 15 years old) consumed up to four times more electricity than 3 star labelled units [Khosla,R. 2017]. To understand adoption of LED lamps in households, Prayas Energy group's study in semi-urban Uttar Pradesh and Maharashtra reveals that in UP, 68% of households used only LEDs whereas in Maharashtra 54% used a combination of LED and CFL. The possible reason behind the difference being the previously run programs in Maharashtra to promote CFL [Prayas Energy group, 2019].

Another study using appliance stock method (quantity, power consumption and usage hours similarity), observed that appliance stock had 93% correlation with electricity consumption [Murthy, K. N.2001]. Letschert and McNeil of the Lawrence Berkeley National Laboratory (LBNL) calculated consumption by multiplying the appliance stock and usage per appliance while estimating potential savings in electricity by Indian households over the period from 2000 to 2030. The saving per appliance was estimated based on calculated difference between projected usage (based on present consumption) and energy efficient model. In a similar study with residential households, it was estimated that by shifting to energy efficient model, there would be an annual saving of 57 TWh which would not be possible in a business-as-usual situation [Prayas Energy group, 2016], proposing an urgent need for better penetration of energy efficient appliances in households.

Need for ground level granular data on REC in India

India does not have a formal Residential Energy Consumption Survey (RECS) unlike developed economies. Data on ownership of different appliances [Prayas Energy Group, 2016] is captured to some extent in census and NSSO's survey on consumer goods. The periodicity and the data coverage of those surveys are few and far between than needed to understand the emerging trends. Ground data on appliance ownership, their usage, and impact on consumption, relation to policies / schemes, are missing today. Without these, India's ambitious goals to climate change initiatives and SDGs may not gain ground as electricity generation's contribution to

GHG emissions is very high, even after accounting for its ambitious renewable energy targets.

This paper builds on valuable ground data directly collected from consumers in two cities (Bangalore, and Chennai) on REC. It takes a statistical approach and hence avoids biases. Such a study should help in obtaining insights about the role of electrical appliances in REC, particularly revealing opportunities for promoting energy efficient appliances.

DESIGN OF THE STUDY

The unique aspect of VR is its field level data driven approach motivating household consumers to voluntarily participate and share information on their electricity consumption. Statistically valid sampling methods were used to ensure adequate representation of households as explained in this section.

Choice of cities

VR program was launched as a pilot study in Bangalore in 2015 and has since grown organically to more than 4000 households in mid-2019. VR was piloted in Chennai in 2018. Table 1 lists some characteristic features that led to the choice of the cities and the samples therein.

Cities / Character	Climate*	Average Number of households**	Population density (Per sq. km)**
Bangalore	Temperate	12,72,413	12,000
Chennai	Warm - Humid	11,06,567	26,553

Table 1: Characteristics of the selected cities

**Based on BEE ECBC 2017*

BHK (Bedroom Hall Kitchen) as a common classifier

Getting floor area information from households was not reliable as observed in an earlier VR pilot in Bangalore. This necessitated the use of a more conversational classifier and BHK was one such common use terminology prevalent in India. Even though floor area to BHK mapping varies from city to city, BHK has proven to be a reliable though proxy indicator of relative floor space and affordability within a city for this study.

BHK can be interpreted as the dwelling room that the Indian Census uses to ascertain household sizes. Other studies have analysed and found dwelling and household size as likely predictors of electricity consumption. [Huebner, G et.al, 2016].

Electrical consumption indicators

The annual average consumption in units and per capita annual average consumption in units are the primary indicators. The program obtains the consumption data in units (kWh) from the electricity utilities and this is available as monthly data for Bangalore and bi-monthly data for Chennai. The annual averaging ensures that the analysis is not biased by factors like seasonality, locked houses, etc. The program also computes per capita data, using the occupancy of the house collected during the survey.

However, for the purpose of correlation study covered in this paper, only the annual average consumption is used. For this study done in July 2019, data of past 12 months was considered as the annual average.

Sample size and distribution:

For any study, if the population universe is in lakhs, then around 400 randomly chosen respondents present a good sample size for a 95% confidence level and a 5% margin of error[1].

VR participation in Chennai is 609 households and has crossed 4000 households in Bangalore. The recommended sample sizes of the respective categories were selected based on census 2011 figures of BHK wise households in the respective cities (Tables 2 and 3).

Dwelling rooms	No of Households in Bangalore district	% of total	VR coverage	VR % of total
No exclusive rooms	166393	7%		
1 BHK	789182	33%	1894	50%
2 BHK	753526	32%	1405	37%
3 BHK	437378	18%	473	12%
4 and 4+ BHK	230574	10%	38	1%

Table 2: BHK-wise households in Bangalore and VR coverage

Dwelling rooms	No of households in Chennai district	% of total	VR coverage	VR % of total
No exclusive rooms	26177	2%		
1 BHK	427430	39%	130	21%
2 BHK	339257	31%	256	42%
3 BHK	212778	19%	185	30%
4 and 4+ BHK	100925	9 %	38	6%

Table 3: BHK-wise households in Chennai and VR coverage

The participation from households was not controlled based on number of occupants of the households. However, the coverage has ensured a reasonable occupancy distribution in the sample (Figures 1 and 2, the numbers 1 to 10, denoting the actual occupancy in the houses).

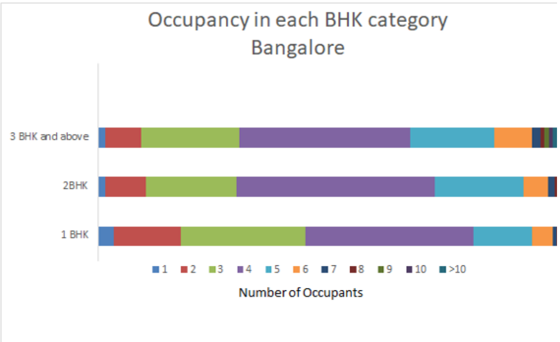

Fig 1: Occupancy among VR participating households in Bangalore

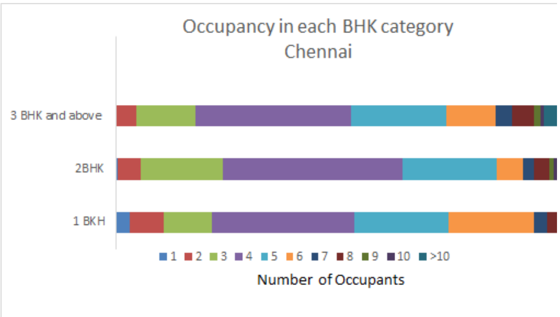

Fig 2: Occupancy among VR participating households in Chennai

EXECUTION OF THE STUDY

Registration for the program

Participation in VR requires registration, which can be done through a mobile app or through the stewards. Stewards are youth selected and trained in conducting home electricity surveys. Registration drives are conducted in various corporates, institutions, apartments through awareness sessions. Stewards undertake door-to-door registration in selected areas.

On registration, an awareness booklet on electricity conservation is given to the consumer. The same is available on mobile app also.

Survey questionnaire

Once registration is done, the participant is asked to take a survey.

After a few rounds of iterations, VR has settled on a questionnaire format divided broadly into three parts:

Part I: Consumer profile information and includes account no, sanctioned load as mentioned in the electricity bill, Location pin code, Mail ID for correspondence, BHK, Occupancy, type of residence and some socio-economic indicators.

Part II: Information on the various types of electrical appliances (lighting, heating, cooling, kitchen, entertainment), usage pattern, peak hour usage and penetration of solar appliances.

Part III: Consent from the consumer for obtaining consumption data from the supplier, promising data security and confidentiality.

Thus, the appliance data is directly collected from the participant.

Obtaining consumption data from utility:

As consumers have difficulty recalling past consumption and the program tracks the consumption of the participant, the electricity account IDs of the participants are used to obtain the consumption data directly from the supplying utility. This is done based on the consent given by the consumer in part III of the survey questionnaire described above. In the case of Bangalore, the data is obtained from Bangalore Electricity Company (BESCOM), and from Tamil Nadu Generation and Distribution Corporation (TANGEDCO) in Chennai.

Data confidentiality, privacy and security:

The data is obtained from BESCOM through an NDA protecting the personally identifiable information of consumers by both parties. TIDE follows prescribed standards for data privacy and data security (developed in line with national and international standards). The personal data collected is secured in an independent cloud platform following due security protocols. The data is not used by TIDE for any other programs or shared with any other partner. TIDE uses only anonymised aggregated data for all presentations

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and papers. Personal information like name and address are used only to send household electricity reports.

Data Analysis

The need for data cleaning is limited in VR due to the automated process of administering the questionnaire and recording answers in the mobile app. Still the data is standardized, validated, and scrubbed for duplicates. After merging the data directly collected from the consumer with consumption data obtained from the utility using the account ID, the data set is processed in categories of BHK within each city. The bottom and top 10 percentile households are not considered for aggregate analysis as they are treated as outliers. Such cases occur in practice due to many reasons like locked houses, billing errors, etc.

For understanding seasonal effect, monthly average temperature data for the respective cities was obtained from open sources. [world weather online, 2019]

Home report generation

For generating individual customized home electricity reports, each home is benchmarked based on the following models [Krishnan Sumathy, et al., 2017]:

a) **Understanding own consumption pattern historically**

b) **Understanding where the household consumption stands vis-a-vis neighbours**

c) **Understanding the break-up of consumption based on the categories like lighting, heating, cooling, etc**

Households report nudges them to set a goal for consumption with these benchmarking and provides customized recommendations to bring down consumption or transitioning to efficient appliances. Apart from the above, best practices already being followed, safety recommendations, tariff slab-based analysis are provided in the report to reinforce conservative behaviour.

For aggregated analysis

For each city, average annual consumption and per capita consumption is aggregated for each BHK category to arrive at the city level and BHK level benchmarks. One of the unique aspects of the VR program is the generation of such benchmarks in residential electricity consumption, emerging from field level data. Additionally, there is rich data on appliances and an attempt has been made to correlate the consumption with electrical asset ownership in different BHK categories in both cities.

Presently this analysis is used only to rank assets in order of their likely impact on consumption. It is possible to derive an analytical equation predicting the impact of assets on consumption, which is not in the scope of this paper.

RESULTS AND DISCUSSION:

After removal of Outliers, 3310 households in Bangalore and 572 households in Chennai qualify for the analysis on correlation of electrical appliance ownership to the consumption.

The range of consumption at the 10^{th} and 90^{th} percentile is tabulated in Table 4.

City	BHK Category	Annual electricity consumption in kWh	
		10^{th} percentile	90^{th} percentile
Bangalore	1 BHK	258	1828
	2 BHK	434	2660
	3 BHK and above	854	4531
Chennai	1 BHK	818	2998
	2 BHK	1228	5236
	3 BHK and above	1481	8650

Table 4: Distribution of consumption of VR consumers across the BHK categories and cities

This study uses data falling between the 10th and the 90th percentile value with respect to annual average consumption.

Figure 3 shows the BHK wise average annual and per capita consumption (kWh) of participating households of Bangalore and Chennai.

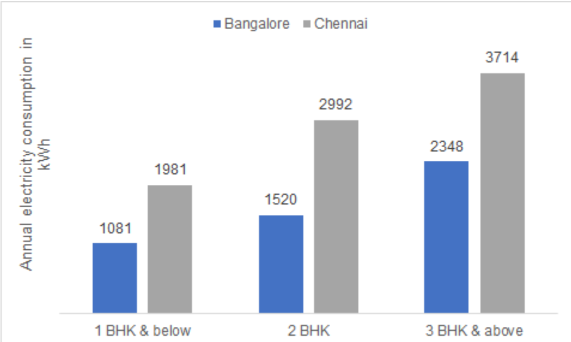

Fig 3: BHK wise average annual electricity consumption (in kWh)

This study will use the city wise BHK wise average annual consumption for correlating with electrical appliance data.

Trends in appliance ownership

In each of the cities, the appliance holding average was computed within the BHK categories. In Tables 6 and 7, those appliances with high holding average across different BHKs are listed with their average holding values.

Appliance	1 BHK	2 BHK	3 BHK and above
LED bulbs	1.41	2.65	4.82
Energy Efficient Tube lights	0.22	0.38	1.53
Storage type geyser	0.09	0.48	1.29
AC with star rating	0.0005	0.007	0.05
Refrigerator	0.62	0.92	0.96
Non-Cathode ray TV	0.49	0.92	1.78
Instant geyser	0.03	0.10	0.24
Incandescent bulbs	0.73	0.94	1.72
AC without star	0.00	0.006	0.07

Table 6: Selected electrical appliances and their holding average in different BHKs in Bangalore

Appliance	1 BHK	2 BHK	3 BHK and above
LED bulbs	1.38	2.1	4.3
Energy Efficient Tube lights	0.60	1.28	2.32
Storage type geyser	0.07	0.13	0.30
AC with star rating	0.26	0.80	1.67
Refrigerator	0.77	1.01	1.15
New model TV	0.72	0.92	1.47
Instant geyser	0.18	0.24	0.51
Incandescent bulb	1.81	1.89	2.27
AC without star	0.04	0.16	0.35

Table 7: Selected electrical appliances and their holding average in different BHKs in Chennai

While LED bulbs are prevalent across the BHKs in both cities, the penetration of energy efficient tube lights is high in Chennai across the BHK categories compared to Bangalore. Whether this is due to policies or awareness needs investigation. The presence of incandescent bulbs along with LED bulbs indicates a mixed-use pattern, particularly in Chennai.

Absence of energy efficient fans in the list in both cities (due to a very low holding average) seen in contrast with the large LED penetration, shows the huge potential in this category. This finding corroborates a study done in 2017 which shows less than 1% penetration of energy efficient fans in households of Kerala [Jayaraman C, Sathaye.J, SasiK K, 2017]. The shift to energy efficient choices as in lighting sector has not happened with fans. This is an intent versus knowledge gap highlighted in Prayas Energy Group's study arguing that fans are rarely part of the energy efficient discussions, even though they are the most common electrical equipment [Singh D et al.2010].

We observe high penetration of star rated ACs in all BHK categories in Chennai compared to Bangalore. Bangalore shows relatively low holding of ACs. It also points to a possible opportunity to promote energy efficient fans in place of ACs in Bangalore, resulting in significant savings by replacing the old fans (>10 years).

The holding of storage type geysers is relatively low in Chennai, while there is significant holding of instant geysers.

NOTE: While Chennai data is pertaining to 2018 and later, some data in Bangalore is from 2015. Attempts are on to update these through a feedback study and through the mobile android application.

Correlation between electrical appliance holding and electricity consumption

Correlation coefficient analysis was done to find out the relative contribution of the electrical appliances to the annual average electricity consumption. For every participant, the holding value of each appliance is multiplied with the rated wattage and correlated with the annual consumption. The correlation index was then computed for participants in each BHK category for every appliance (with respect to consumption). Tables 8 and 9 show the electrical appliances ranked within each BHK category (**value of correlation index is mentioned in brackets**) in decreasing order of their correlation to consumption, for both the cities. Note that (i) sample sizes are different for Bangalore and Chennai and is not normalized as the correlation is done for every participant and (ii) consumption data is not normalised for seasonal variations in both cities.

Bangalore

Rank	1 BHK	2 BHK	3 BHK and above
1	Tube light (0.17)	Storage type geyser (0.10)	LED TV (0.23)
2	Refrigerator	Incandescent	Tube light

	(0.17)	bulb (0.07)	(0.21)
3	Storage type geysers (0.16)	AC with star rating (0.07)	Energy efficient tube light (0.14)
4	LED TV (0.14)	LED bulbs (0.07)	Fan (age less than 10 years) (0.10)
5	LED bulb (0.135)	Refrigerator (0.04)	Fan (age more than 10 years) (0.10)

Table 8: Ranking of electrical appliances in decreasing order of correlation with electricity consumption across BHKs in Bangalore

Chennai

Rank	1 BHK	2 BHK	3 BHK and above
1	Tube light (0.24)	AC with star rating (0.30)	AC with star rating (0.47)
2	Refrigerator (0.15)	AC without star rating (0.29)	Tube light (0.27)
3	AC with star rating (0.13)	Energy efficient tube light (0.27)	Storage type geysers (0.25)
4	Fan (age more than 10 years) (0.12)	Refrigerator (0.24)	CFL bulbs (0.22)
5	Storage type geyser (0.10)	Storage type geyser (0.24)	Energy efficient tube lights (0.18)

Table 9: Ranking of electrical appliances in decreasing order of correlation with electricity consumption across BHKs in Chennai

Considering different climatic profiles affecting the usage of electrical appliances, a comparison of the correlation between the two cities is not justified.

Bangalore:

The presence of tube lights in the top two positions in 1 and 3 BHKs is of interest to note. This category of tube lights is only the fluorescent ones and not the energy efficient ones. The incandescent bulbs contribute to the overall consumption significantly in 2 BHK households indicating an opportunity for LED bulbs upgrade programs.

The absence of refrigerator in the top five for the 3 BHK possible indicates the dominance of other appliances in 3 BHK households.

Storage type geysers play a predominant role aligning with Bangalore’s temperate weather needs. However, its absence in the top five in the 3 BHK category again indicates the dominance of other appliances.

We observe LED TVs as high contributors to total consumption as compared to even AC in 3 BHKs; this corroborates with the high holding value (>1). indicating multiple TVs in the same house.

Fans aged over 10 years contribute significantly to 3 BHK ranked in the Top 5 appliance. While 1 and 2 BHK households also have old fans, they are not significantly contributing to consumption. This indicates a potential consumer base for targeting for efficient fans, especially considering the low holding in all categories.

Chennai:

In Chennai, cooling appliances especially ACs with star rating have higher correlation with consumption in all categories which corroborates previous studies on the REC [Prayas energy group,2016].

As in Bangalore, the refrigerators are not in the top five in the 3 BHK category.

Tube lights (Non-LED) contribute to significant lighting load in all categories showing low penetration of energy efficient tube lights. The presence of CFL bulbs in 3 BHK shows the opportunity for replacement with LED bulbs

Water heating by use of storage water heaters are significant contributors in all categories. Policy initiatives to promote alternates like Solar water heaters or star rated geysers could help conservation.

CONCLUSION

As aspirations drive more consumption and uptake of electrical appliances, motivating consumers to transition to efficient appliances are becoming a necessity. Evidence based programs VR provide valuable insights that can help in this transition through right targeting and messaging.

The insights available through this study can be used for scaling uptake of affordable and efficient appliances through different business models (e.g. rolling out superefficient appliance programs). Such an effort is the need of the hour in India, considering our unique challenge to balance economic development with environmental conservation commitment.

While more data and detailed analysis will strengthen the interpretations, the correlation analysis highlights the need to have disaggregated data for policy making in dissemination of efficient appliances.

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ASSESSING THE BENEFITS OF CHANGEOVER CONTROL ALGORITHMS IN MIXED-MODE RESIDENTIAL BUILDINGS IN INDIA THROUGH CO-SIMULATION

Saranya Anbarasu[1], Yash Shukla[1], Rajan Rawal[1], Deepta Mishra[1], Jayamin Patel[1], Charalampos Angelopoulos[2], Malcolm Cook[2], Luciano C de Faria[2], Dennis Loveday[2]

[1]Center for Advanced Research in Building Science and Energy, CEPT University, India

[2]School of Architecture, Building and Civil Engineering, Loughborough University, UK

ABSTRACT

Rapid urbanization, rising per capita income and a warming climate are significantly increasing the burden on the electricity grid throughout India(Rawal and Shukla, 2014). The combined use of natural ventilation (NV) and mechanical cooling (MC) systems is a potential solution to provide cooling and thermal comfort to building occupants. Mixed-mode (MM) buildings use NV and MC to provide a comfortable environment for the occupants. Past studies have established that many Indian residences operate in temporal and spatial MM. Existing algorithms used in MM buildings to changeover between NV and MC modes are unsophisticated often leading to inefficient operation. In most cases, the changeover algorithm determines operation mode based on a predefined temperature or based on the occupancy schedule. This paper assesses the benefits of sophisticated changeover control algorithms in a MM residential building. The paper first develops two control algorithms, with varying degrees of complexity, suitable for mixed-mode residential buildings. Further, the benefits of the developed control algorithms are assessed for four climate zones of India using the dynamic thermal simulation model. This paper uses the Functional Mock-up Interface (FMI) to couple Modelica and EnergyPlus as well as to exchange data for co-simulation. The results demonstrate that there is a positive comfort benefit with 76% to 98%lesser uncomfortable hours and 6% to 24% energy savings for the developed algorithms compared to the reference in the 4 climates zones.

Keywords—Mixed-mode Buildings, Building Energy Simulation, Residential Buildings, Building Controls.

INTRODUCTION

Currently, buildings are responsible for around 35% of India's total energy consumption, and this is increasing by 8% annually(Rawal et al., 2012). In the case of a country with a predominantly hot climate, occupants use air-conditioning(AC) systems to maintain thermal comfort. For example, Space conditioning not only consumes an enormous amount of energy, with the implicit cost (Krausse, Cook and Lomas, 2007) but also increased greenhouse gas emissions(Vangtook and Chirarattananon, 2007). While natural ventilation(NV) can be an effective cooling approach at favorable outdoor conditions, it will lead to discomfort of the occupants under extreme weather conditions(Baker and Standeven, 1996). Thus, the combined use of both natural ventilation and mechanical cooling systems is a potential solution to provide cooling, ventilation, Indoor Air Quality (IAQ), and thermal comfort for the occupants inside the building(Salcido, Raheem and Issa, 2016). Mixed-mode(MM) is an approach of space conditioning by means of natural ventilation or mechanical cooling at different times of the year, whichever is feasible(Wouters et al., 1999). Many buildings have been operating as mixed mode, but they miss out on the familiar benefits of operable windows. There have been proven benefits of energy savings ranging from 22%-77% (Chen, Tong and Malkawi, 2017) from a code-compliant building in various climates. With wind speeds higher than 0.2 m/s, occupants feel comfortable with air temperatures 2°C higher than the ASHRAE comfort range(Nicol, 2001). In practical situations, manual operation is very tedious as the windows must be operated by the occupant decisions. On the other hand, automated controllers are expensive and require a carefully drafted control strategy to perform as intended. The lack of predictability, modeling natural ventilation impact, control over indoor conditions, lack of access to operational standards and protocols have made mixed-mode(MM) operations a challenge.

EXISTING MIXED MODE CONTROLS

Existing Case studies

CBE (Center for the built environment, UC Berkeley) has developed a database of 530 mixed-mode buildings where the design and operation strategies of each building have been documented (Brager G, Borgeson S, 2007). Most of the buildings in the database operate either as zoned or concurrent mixed mode. Only twenty-one case studies operate in change over type MM. The following table shows details of the controls in various buildings from the database.

Table 1 Case studies with MM control strategies

No.of. Case studies	Control type	Description
5	Temperature differential	Based on the indoor and outdoor temperature difference
1	Seasonal schedule	Summer and winter had a different schedule for window operations
2	Pressure differential and wind velocity based	Windows opened or closed based on the pressure differential between the openings and wind speed.
2	CO2 based	The windows switched based on the CO2 concentration in the occupied space.
9	Manual switching	Control decisions conveyed through red and green lights in the zone to open/close the window.
6	Louver degree of opening control	The louvers of the windows and vents were opened in various degrees based on the requirement of ventilation to space.

Existing research on the MM control algorithm

There is a lot of theoretical research for MM controls as per the state of art research(Gandhi, Brager and Dutton, 2015). Model predictive controls by Roetzel, Tsangrassoulis, Dietrich, and Busching, (2010) estimates the occupant's behavior for window control operations through the "most likely" pattern of aggregate behavior. Eftekhari and Marjanovic (2003) executed their research using fuzzy logic control with verbal descriptions and decisions to achieve thermal comfort. An SMPC (Stochastic model predictive control) indoor air temperature-based control developed by Mady predicts the window operations based on stochastic disturbance for occupant presence(Mady et al., 2011). Adding to this, Haldi and Robinson (2011) tested a simulation-based model coupled with actuators based on the indoor-outdoor temperature differential. Nicol (2001) proposed the usage of a probability distribution for window state controls based on the temperature gradient. Rijal et al., (2008) evolved the "Humphreys window opening algorithm," which used multiple logistic regression based on outdoor and indoor temperature combined with an opening and closing actions. Most of the research focused on occupant behavior and temperature gradient. Though there have been advanced trained MPC, stochastic and probability-based predictions for window opening, there needs for sophisticated algorithms that can determine suitable operation mode of a change over MM buildings.This paper focuses on developing building physics-based algorithms to determine suitable MM operations. The outcome of this research is a sophisticated algorithm for a single thermal zone building with generic envelope and occupant schedules. The algorithm will need modifications when implementing into real buildings.

METHODOLOGY

There are three major steps to the methodology. The first step identifies the potential control parameters and strategies to be considered for control. It also establishes reference algorithms used in selecting the operation mode of the changeover MM buildings. Two reference algorithms from literature which are based on indoor-outdoor temperature difference(Figure 5) and weekly schedule respectively are used to compare the performance of the two developed algorithms(Figure 6).

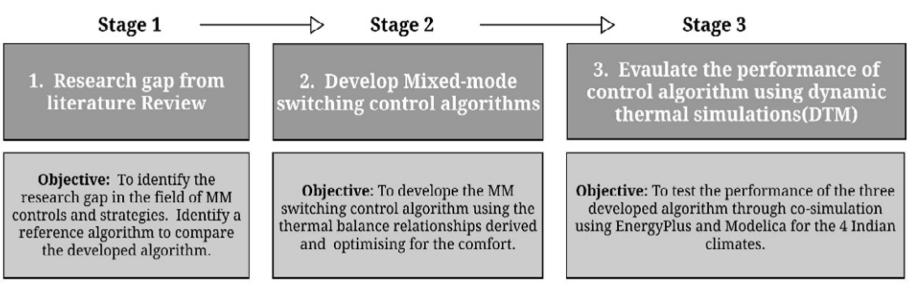

Figure 1 Research Methodology

Development of control algorithm

In the second step, the key performance parameters on which the NV-AC switching in mixed-mode buildings depend, along with the key input, output, and control variables are identified. A generic equation is developed with the input variables for area, envelope specification, internal gains, schedule, and air change rates using building physics(ASHRAE fundamentals 2009, EnergyPlus engineering reference 8.8). From the derived relationships, the algorithm flow charts were developed. In the developed algorithms, the thermal balance approach is used to determine the suitable operation model. In this approach, it is assumed that the total heat gained inside a single zone thermal space is equal to the heat generated (includes the external heat gains from the envelope and internal heat gains from occupants, lighting and equipment) and the heat removed or added (due to natural ventilation and infiltration)(Figure 2).

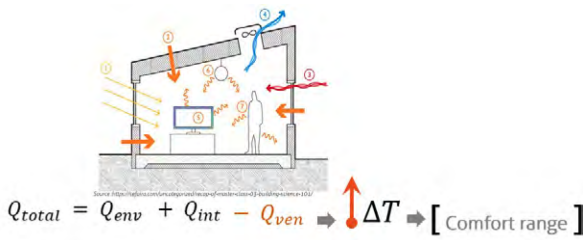

Figure 2 Concept of Thermal Balance

The control algorithm first predicts the internal and external gains of the zone. This total heat gained in the zone is expected to lead to an increase/decrease in the indoor temperature.

1. If the predicted indoor temperature is within the temperature range, as determined by the IMAC MM model when the windows are opened, and the loads in the space are met through natural ventilation.
2. If the predicted indoor temperature of the space is higher than the comfort band temperature, then loads need to be met through air conditioning.
3. If the loads are met without the window open or AC ON, then space is comfortable by free-floating (FF). The control algorithms aim to operate the building in NV and FF mode when the conditions are favorable to achieve energy savings.
4. The algorithm first checks for FF mode, then NV mode and finally AC mode for strategical MM operations.

The heat extracted due to ventilation considers the airflow due to both pressure and temperature gradient. The control decisions are made based on operative temperature, instead of air temperature, as it includes both the radiation and convective component that the occupant could sense.

Comfort model

The Indian Adaptive Thermal Comfort Model (IMAC), which is derived through empirical field study specific to the Indian context, provides neutral temperature and acceptability limits for air-conditioned, natural ventilation and mixed-mode buildings(Manu *et al.*, 2016). To assess the comfort of the space, threshold values are referred from IMAC mixed-mode comfort model and for the ventilation standards, ASHRAE 62.1 is referred. 90% MM acceptability limits with neutral temperature +/- 3.46 ˚C are used for taking the control decisions in the algorithm. To compare the reference algorithms the comfort band of +/- 2˚ C from the static setpoint of 24.4˚C is used (ASHRAE 55).

Evaluating the performance through Co-simulation

A single zone building, with envelop specifications(Table 2) is modeled in DesignBuilder(Figure 3). The envelope characteristics

Table 2 Description of the climate chamber at CARBSE

Dimensions	5.65 X 4.65 X3.25	in m
Window size	1.2 X 1.2	in m
No of windows	1	
Envelope	U value	
Wall	0.344	W/m2K
Roof	0.44	W/m2K
Window	5.788	W/m2K
SHGC	0.819	
Internal gains		
Occupant	2 Nos	NBC 2016
Lighting	4 W/sq.m	ASHRAE 90.1-2010
Equipment	5.1 W/sq.m	GBPN Report
Schedules	Hourly	ASHRAE 90.1-2010
Ventilation and Air-conditioning		
HVAC system	Split AC	COP-3, 1.5TR
ACH nat	2.3/hr	(Bhisti, 2018)
Stack Coefficient	0.0001456	ASHRAE 2009
Wind Coefficient	0.000104	ASHRAE 2009
Effectiveness of opening (Cv)	0.25	ASHRAE 2009
Discharge coefficient (Cd)	0.45	Calculated

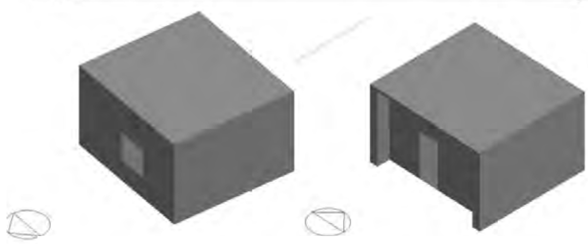

Figure 3 Climate chamber model in DesignBuilder

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of the simulation model are aligned with an existing chamber at CARBSE at CEPT University for future validation experiments. The occupant, lighting, and equipment schedules are referred from ASHRAE residential standards. Four cities are chosen for the 4 representative Indian climates [Ahmedabad-Hot dry(HD), Mumbai- Warm and humid(WH), Delhi-Composite(CO), Bangalore – Temperate(TM)].
The output of DesignBuilder a .idf file containing all the input details of the model is exported to EnergyPlus to add details of the HVAC system, schedules, export variables, and output variables. The .idf file, epw (weather file), EnergyPlus .idd file are combined using the python script (EnergyPlusToFMU) to create a.FMU file.

The created FMU is imported in Dymola, which is a Modelica interface. Modelica is an equation-based object-oriented language for system modeling and simulation developed by Fritzson & Engelson (1998). Models are described by differential, algebraic and discrete equations(Wetter, 2009). Co-simulation allows extending the capabilities of different domain-specific simulation programs through the run-time coupling with other simulation programs, for lesser computing time and ease-of-use (Wetter, 2011).

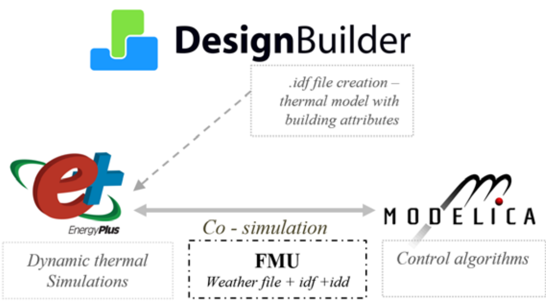

Figure 4 Co-simulation Process

The developed control algorithm is implemented in Modelica with an FMU import of the single zone space (Figure 4). The developed and reference algorithms are coded into Dymola and the simulations are performed on various time scales such as annual, monthly, daily and hourly. The operative temperature from the simulation result of the four algorithms is compared with the IMAC MM comfort band to calculate the number of comfort hours. The energy consumptions of the control algorithms are compared to evaluate the best performing algorithm in the representative climate zone considered. These two comparisons decide the feasibility of the algorithm in that specific climate.

ALGORITHMS

The temperature and schedule based algorithms are the reference algorithms from literature. The temperature based algorithm is used as the base case to compare the performance of other algorithms. The simple and detailed algorithms work on the principle of thermal balance, and vary with the number of input sensors. Table 3 describes the logic,number of inputs and outputs of all the four algorithms.

Criteria for evaluation

The MM switching control algorithms are evaluated for effective performance based on the following parameters:

1. The number of comfortable hours in a year (out of 8760 hours).
2. Annual and monthly energy consumption.

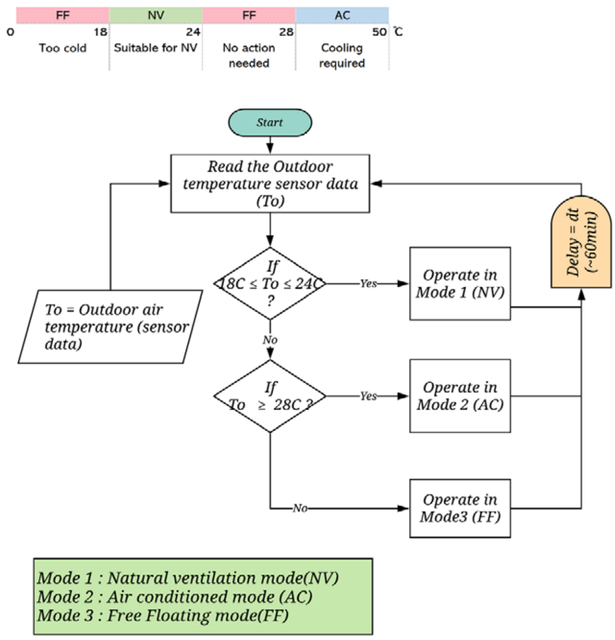

Figure 5 Algo_Temp [Reference algorithm]

Table 3 Details of the reference and developed algorithm

Algorithm	Type	Logic	Inputs	Outputs	Setpoint
Algo_Temp	Reference	Switching based on Indoor outdoor temperature difference	2	2	Static [24.4°C]
Algo_Sch	Reference	Swithching based on pre-defined weekly schedule	Nil	2	Static [24.4°C]
Algo_Smp	Developed	Switching based on Thermal balance	5	3	IMAC MM Setpoint
Algo_Det	Developed	Switching based on Thermal balance	9	3	IMAC MM Setpoint

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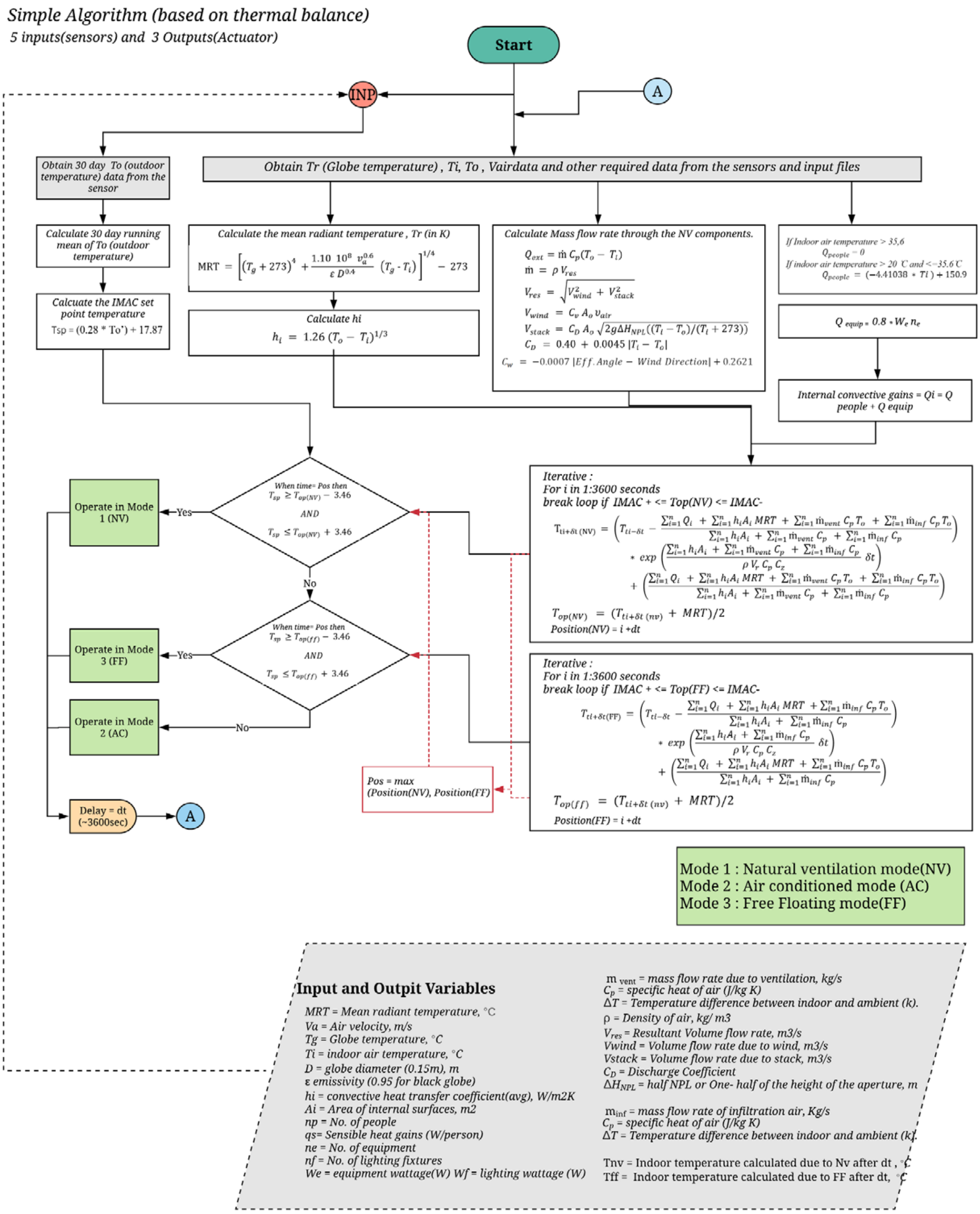

Figure 6 Algo_smp [Developed algorithm]

RESULTS

Results of the Hot and Dry climate(Ahmedabad) is described in detail in the following section. The summary of performance in all climates follows later in this section.

Comfort performance[HD]

The uncomfortable hours and energy consumed every month for all the four algorithms are represented in Figure 7. It is observed that the uncomfortable hours in the case of Algo_sch is above 400hrs for 4 months[Jan, Aug, Sep, Oct]. The uncomfortable hours in the case of Algo_temp also follow a similar trend. The annual uncomfortable hours of both the reference algorithms are above 1900hrs. This is about 20% of the total hours in a year. Whereas, the two developed algorithms, Algo_smp and Algo_det perform very similar in terms of comfort and energy. There is a 98% reduction in the uncomfortable hours compared to the reference algorithms. It can be observed that the maximum uncomfortable periods for developed algorithms that occurred monthly is 9hrs and is during summer months. Hence better control logic and parameters lead to a reduction in the uncomfortable hours. To understand when these uncomfortable hours occur in the year for the four algorithms, heat maps are plotted on an hourly scale in figure 8.

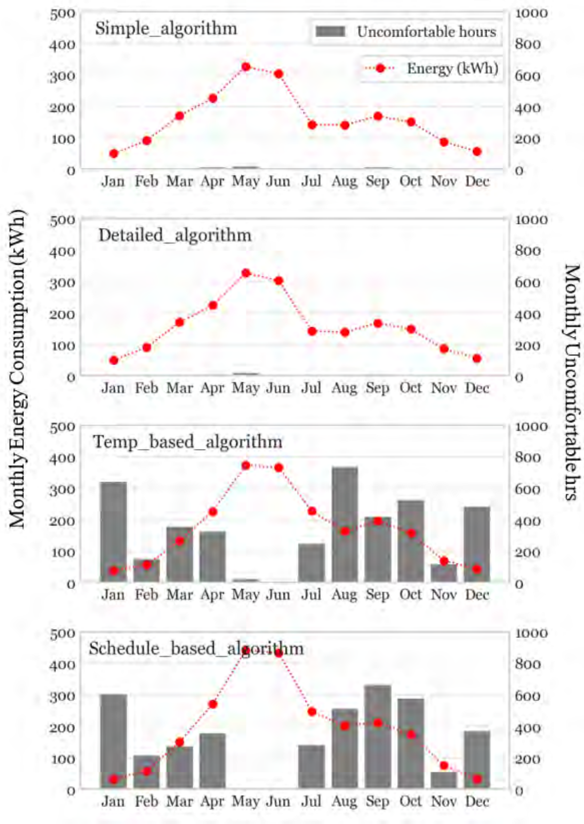

Figure 7 Monthly uncomfortable hours

In the heat maps, the green represents the comfortable hours and the orange represents the uncomfortable hours. Since the building is operated as residential, there is complete occupancy from 1-7 hrs and 19-24 hrs. Hours from 8-18 hrs have 0.5 occupancy. It can be observed that for the developed algorithms the uncomfortable hours occur during the partially occupied hours, between 10-12 hrs. In the case of reference algorithms, the peak periods from 12-16 hrs are comfortable due to AC operation,but a large number of uncomfortable hours occur during the occupied periods from 1-7 hrs for Jan-April and Jul-oct. This is mainly due to switching to NV based on outdoor ambient temperature, without considering the indoor conditions. This is also termed as open-loop controls, where there is no feedback from the space to the controller. Hence the decisions are only based on some external reference. Though Algo_temp and Algo_sch differ by instantaneous and pre-defined actions, there is a variation in their occurrence of uncomfortable hours. For Algo_sch there is a consistent occurrence of discomfort periods for every month, which can be greatly avoided with instantaneous switching as in Algo_temp. Thus the developed algorithms have greater comfort benefits compared to reference algorithms.

Energy performance [HD]

The HVAC energy consumed for 8760 hours by the four algorithms is plotted in Figure 9. During the months of Feb and Nov the developed algorithms have few hours of HVAC operations as the setpoint is in the

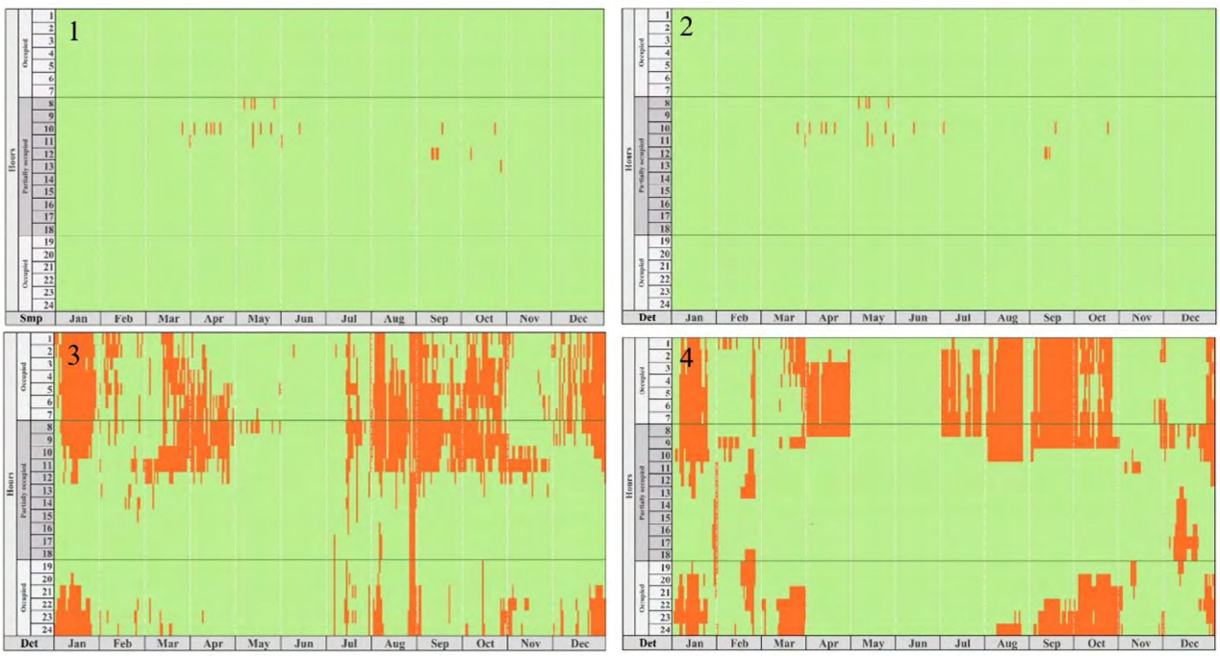

Figure 8 Occurrence of Uncomfortable hours [1] Algo_smp, [2] Algo_Det, [3] Algo_Temp, [4] Algo_sch

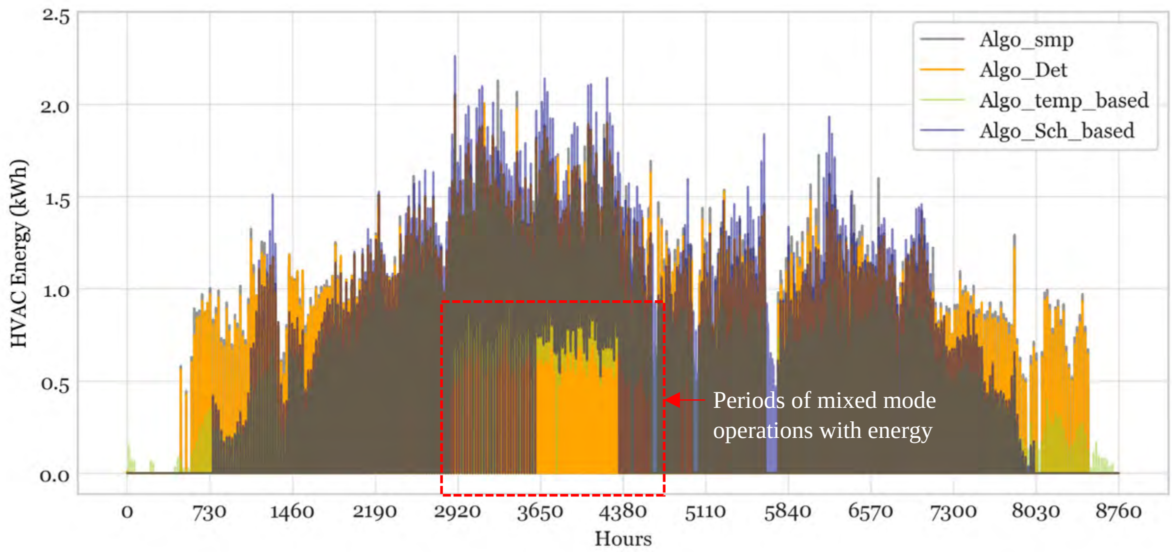

Figure 9 Annual HVAC Energy consumption

range of 22-23°C, whereas the reference algorithms switch ON the HVAC systems only when the outdoor temperature is more than 28°C, thus there is no HVAC consumption. During the months of April to September, the developed algorithms operate as MM with predominant periods of NV, resulting in 14% to 25% lower energy consumption. There is also a 3-4% energy savings during the months of March, October, and November, whereas during December and January there is a 10-22% increased energy consumption solely to maintain comfort .When annual energy consumption is compared there are a 7% energy savings for the developed and 13% increased energy for schedule based algorithm compared to the base case, ie, temperature based algorithm.

ENERGY AND COMFORT BENEFITS IN 4 CLIMATES

The performance of the four algorithms in the four representative climates is summarised in Figure 10. The developed algorithms have similar trends of comfort and energy performance in HD,WH and CO climates.

Algo_sch has the highest energy consumption in all the four climates followed by Algo_temp, similarly the uncomfortable hours. In climates HD, WH and TM through MM control algorithms it is possible to achieve 98% comfort, whereas in CO climate only 92% achieved with 686 uncomfortable hours. Also, the occurrence of uncomfortable hours is during the month of Dec and Jan when heating is mandatory. This could be rectified by incorporating the heating controls in the MM control algorithms. TM climate is found to be climatically favourable for MM operations.

Figure 11 represents the percentage savings for the algorithms compared to the temperature based algorithm(Algo_temp). The objective of the paper is to evaluate the best control algorithm in different climates, hence the annual savings can be an overview metric to assess. Except for the TM climate, the developed algorithms have 7% energy savings in HD, 17.5% in WH and 24% in CO. This shows that the developed algorithms have better control compared to the reference algorithms.

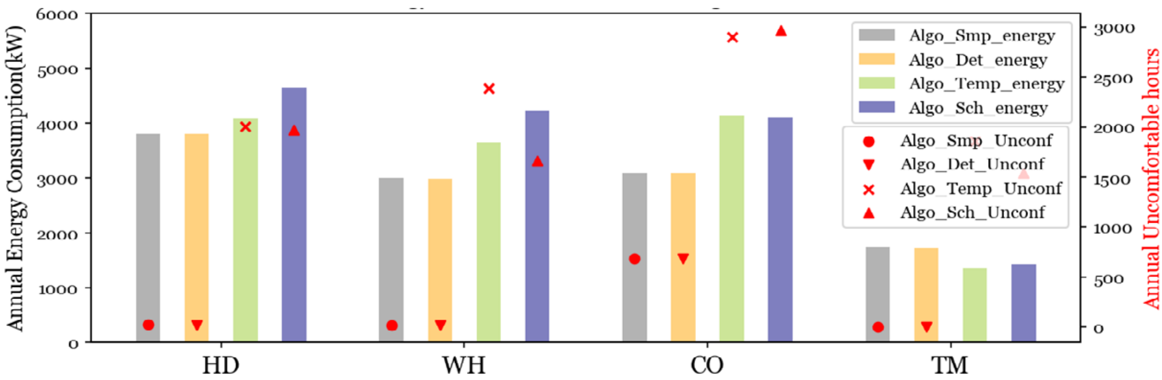

Figure 10 Summary of Energy and Uncomfortable hours [Annual]

Further, there is a 98% lesser uncomfortable hours for the developed algorithms compared to the reference. Thus it is evident that physics-based control is more accurate than the predefined schedule or instantaneous temperature differential based control. For further assessment, humidity could be considered to take nested control decisions. While comparing simple and detailed algorithms, the simple algorithm performs similar to detailed with lesser inputs from the control zone. Thus with a lesser number of sensors as feedback from the space the same precision of control could be achieved. In the real case, the simple algorithm will have a globe temperature sensor to calculate MRT, whereas in detailed there will be 6 sensors on each surface of the space to calculate the heat gains.

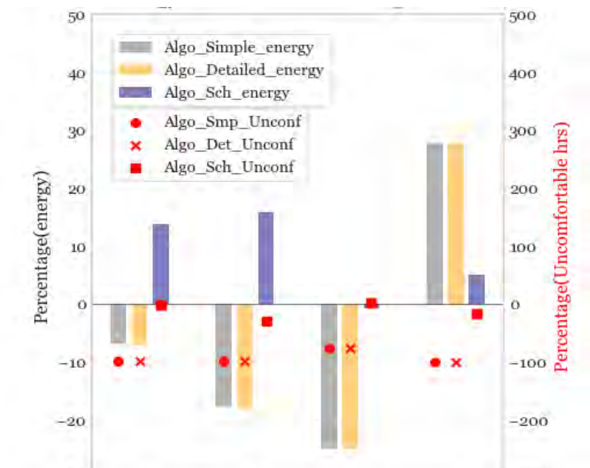

Figure 11 Comfort and energy benefits in percentage

CONCLUSION

The paper presented a novel mixed-mode switchover control algorithm based on thermal balance. The key intentions for the development of the algorithm to predict the benefits of sophisticated control algorithms based on building physics and with the use of adaptive comfort models. The instantaneous controls are feasible but under longer duration control physics-based models are capable of maintaining precision control. The paper demonstrated 7-24% energy savings and 75-98% comfort benefits theoretically. As the intended research is an exploration of theoretical potential due to MM switching control algorithm, the actual savings can be slightly lower in the real scenarios. Practical situations are often uncertain and unpredictable. The proposed controls can predict the next time step situations, but this would change due to a large number of indefinite parameters such as occupancy at that instant, equipment that is switched on, schedules, multizone space conditioning, external wind speeds, direction, etc. Future research includes validation of the savings through the controlled environment experiments.

ACKNOWLEDGEMENT

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A CASE STUDY ON DESIGN OF THERMALLY COMFORTABLE AFFORDABLE HOUSING IN COMPOSITE CLIMATE: SIMULATION RESULTS & MONITORED PERFORMANCE

Saswati Chetia[1], Sameer Maithel[1], Pierre Jaboyedoff[1], Ashok Lall[1], Prashant Bhanware[1], Akshat Gupta[1]

[1]*Indo-Swiss Building Energy Efficiency Project (BEEP)*
New Delhi, India
saswati@gkspl.in

ABSTRACT

New urban housing in India is heavily focused on construction of affordable housing (housing for families belonging to low- and medium-income groups). The design of the new affordable housing should ensure acceptable level of thermal comfort for the occupants without the use of air-conditioning, which majority of the occupants are unable to afford. Thus, proper design of building envelope to control heat ingress and allow adequate ventilation becomes critically important.

The paper presents a case-study of integrating energy efficient envelope and ventilation strategies in a PMAY affordable housing project at Rajkot (composite climate). The project consisted of 1176 dwelling units, each of 33.6 m^2 built-up area. The measures to reduce heat ingress included low U-value walls, shading of windows and partly opaque window shutters. For ventilation, adequately sized casement windows were provided. Building energy simulations (using *EnergyPlus 8.3*) were carried out. After construction, indoor temperatures (air and wall) and natural ventilation were monitored in selected unoccupied flats during the summer of 2019.

The paper presents the design strategies along with energy simulation and monitored results. Maximum average indoor air temperature of 32°C was recorded in the sample unoccupied flat (with proper window opening and closing schedule) during the monitoring period (maximum average ambient temperature of 39°C). The monitored indoor temperatures show good correspndance with the simulated results.

Keywords—Thermal comfort, Affordable housing, Passive design, Performance monitoring

INTRODUCTION

The Pradhan Mantri Awas Yojana (PMAY)- Housing for All (Urban) is Government of India's flagship programme to fulfil the housing demand / housing shortage for the urban poor. This mission target is 12 million affordable houses between 2015-2022, which will be provided central financial assistance / subsidies through the states / UTs with different implementing mechanisms. The targeted construction is almost 11% of the predicted urban residential built-up area, which will house 20-30% of the urban population in 2022 [1].

Heat gains from the building envelope (external walls, windows, roof) play the most significant role in influencing thermal comfort and consequently energy efficiency in residential buildings. Residential buildings have large exposed façade area to built-up area ratio, resulting in the space cooling loads dominated by heat gains from the envelope. The penetration of air-conditioners in residential buildings is low, more so in affordable housing. Thus, design of the building envelope to control heat gains and allow adequate ventilation become vital in maintaining thermal comfort.

The paper presents a case-study of integrating energy efficient envelope and ventilation strategies in a PMAY affordable housing project at Rajkot (composite climate). The project consists of 1176 dwelling units, each of 33.6 m^2 built-up area (**Figure-1**). These flats were designed in 11 towers of 7 storeys with stilt parking (S+7). In 2016, a design workshop was conducted for this project to make it thermally comfortable and energy efficient. The following envelope and ventilation measures were recommended:

- External walls with low U-value
  - 200mm thick Aearted Autoclaved Concrete (AAC) blocks on the east and north side.
  - Cavity wall, constructed of 200mm +200mm thick AAC blocks with 40mm air gap on the south and west sides
- Partially glazed windows
- Window shading (with overhang and side-fins)
- Casement windows were provided, instead of sliding windows, to improve natural ventilation potential
- A common assisted ventilation system was provided to improve ventilation through the flats in case of low wind-speeds. The test results presented in this paper does not include the performance of this system.

Building energy simulations (using *EnergyPlus 8.3*) were carried out to estimate the impact of these measures on internal temperatures.

The project completed construction in early 2019. In May 2019, indoor temperatures and natural ventilation were monitored in selected unoccupied flats.

The results of the above monitoring and the energy simulation are presented, with the focus on impact of the building envelope measures.

MONITORING METHODOLOGY

Monitoring objective

The main objective of the monitoring exercise was to measure the impact of the building envelope strategies and natural ventilation on the internal temperatures of the flats, during peak summer season, and compare it with the simulation results.

Monitoring period

The test was planned to be carried out during a period when the maximum temperature would be consistently above 40°C. Temperature data of the summer months for the last four years (2014-2018) was checked to find this "hot" period. The period between 15th April and 31st May was found conducive, and the test was conducted between 5th May to 31st May 2019.

Selection of the test flat

The test flat was was on 4th floor and faced north (**Figure-1** & **Figure-2).** This flat was chosen for the following reasons:

- It is on an intermediate floor, with windows and opening over north side.
- The general wind direction on the site is from the west. The test flat should be one which does not have direct or "first" access to the wind.

Parameters measured

Table 1 showes the parameters that were measured and the measuring equipment.

Table 1: Details of monitored parameters, instruments and their locations

PARAMETER	INSTRUMENT	LOCATION
Ambient		
Ambient DBT & RH	Rotronic XD-33 Temp+Humi Sensor Transmitter with Weather Shield	Terrace; above the overhead water tank (OHT)
Roof-top wind speed	Wind Speed sensor (WIND-COMBO-1)	Terrace; above OHT
Roof-top wind direction	Wind Direction Sensor (Wind vane type potentiometer)	Terrace; above OHT
Indoor		
Bedroom and living room DBT & RH	Rotronic XD-33 Temp+Humi Sensor Transmitter	Centre of the room
Bedroom and Living room CO2 concentration	E-sense CO2 sensor	Centre of the room

Figure 1: Site plan showing the location of the test flat

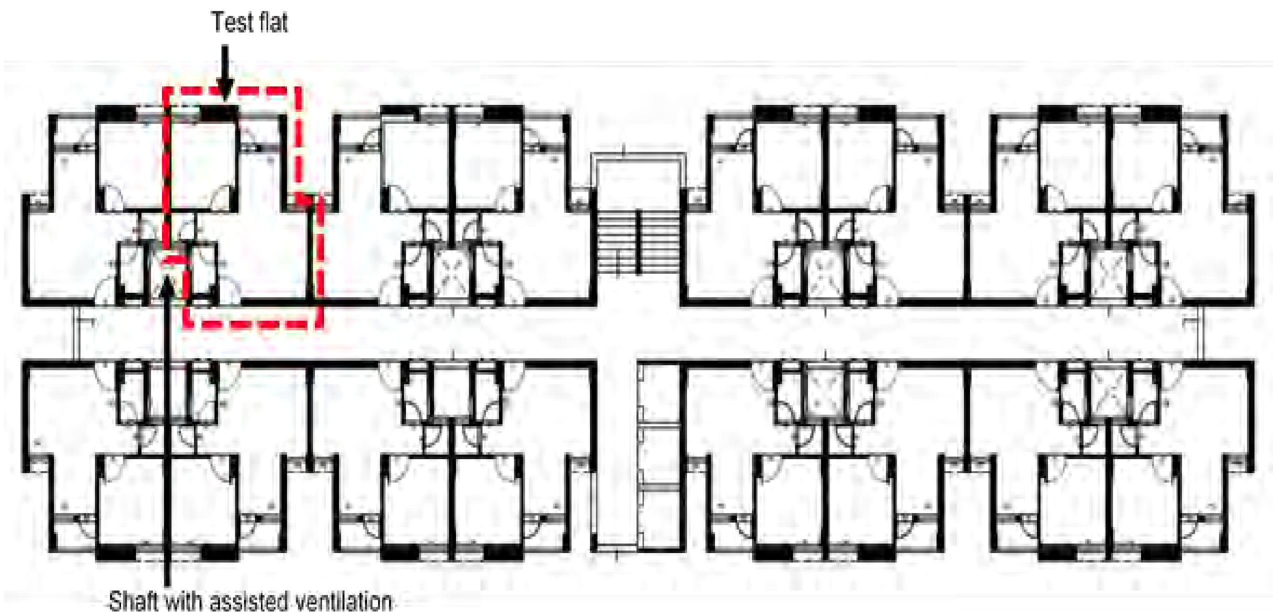

Figure 2: Floor plan of the block with the test flat

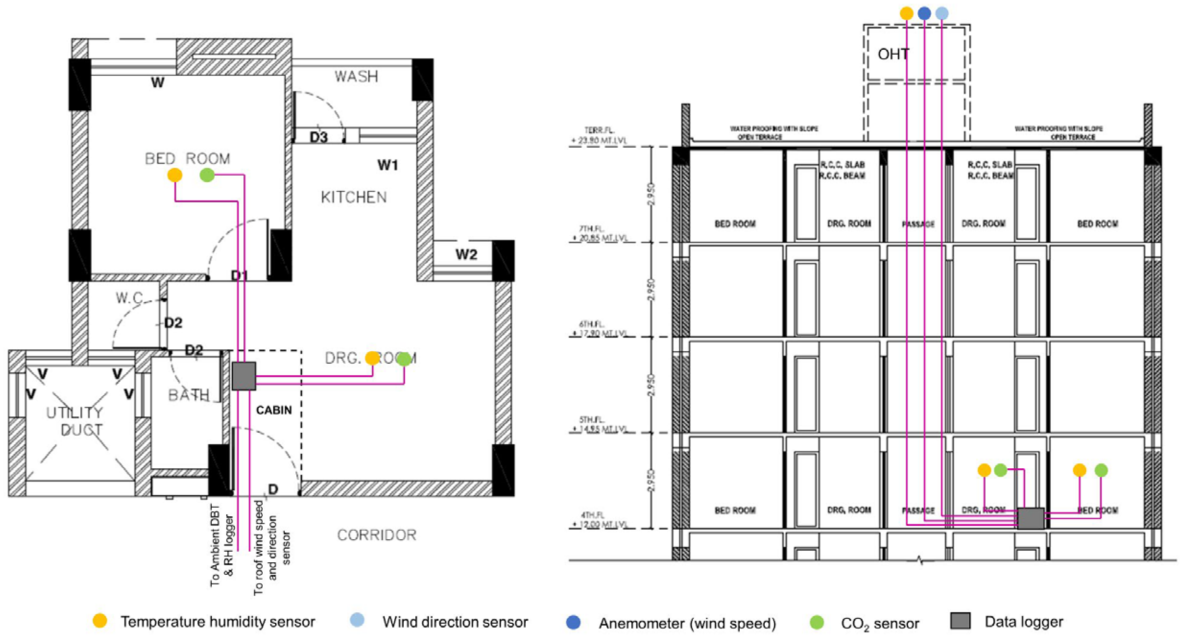

Figure 3: Plan and section of the test flat showing location of sensors and loggers

A 16-channel data logger (SMART SCAN 16 Sunsui Make Universal Input Data Logger with GSM / GPRS) was used to log the above parameters. Frequency of logging was 1 minute. Two ceiling fans in the centre of the bedroom and living room were operated at low speed throughout the measurement period for proper mixing of air.

Test set-up and operation

Figure-3 shows the layout of the equipment. All sensors were connected to the 16-channel logger for continuous logging. A laptop was connected to the logger for display and check. A temporary cabin was installed (**Figure-3**) as an observation area with the laptop and data logger. This cabin isolated the experimental area allowing general observation and scheduled data retrieval without impacting the experimental reading due to presence of human body, CO_2 exhaled by the observers and sudden air-exchange while opening the door.

Continuous logging of all parameters was carried out. The openings were operated as follows:

- The windows of the bedroom (W) and living room (W2) were closed during the day (8 am to 8 pm) and opened at night.
- The entrance door of the flat (D), opening into the corridor, was closed at all times. The louvred opening above this door was also sealed.
- Kitchen window (W3) and wash door (D3) were closed at all times.
- The doors to the WC (D2) and bathroom (D2) were closed. The louvred opening above these 2 doors were kept open.
- The door between bedroom and living room (D1) was kept open at all times.
- The windows of this flat were equipped with mosquito nets.

Calculation of Air Change per Hour (ACH) by constant injection technique

The constant injection technique uses a tracer gas introduced into a room / space at a constant rate and measuring the resulting tracer concentration. The tracer gas used in this case was CO_2 for cost effectiveness, easy availability and for easy replicability of this test in other houses. A constant flow of CO_2 (3.6 NLPM) was injected into the space. In this case, the entire flat, excluding the WC and bath, was considered as one space.

CO_2 sensors placed in the bedroom and living room measured and logged the CO_2 concentration. Average ACH values were calculated for the day (windows closed) and night (windows open), using the following equation [2]:

$$\bar{Q} = \left(\overline{\frac{Q_T}{C}}\right) - \frac{V}{\Delta t}\log_e\left(\frac{C_{final}}{C_{initial}}\right) \tag{1}$$

CO_2 concentration over and above the average ambient concentration of 350 ppm was used in the equation above.

SIMULATION MODEL

To validate the monitored data, computer simulation was done for the period from May 12, 2019 to May 22, 2019. The software used for the simulation was - *DesignBuilder 4.7*, which does energy calculations using *EnergyPlus 8.3* simulation engine. The following are the main modelling inputs required for the computer simulation:

- To simulate the vacant monitored flat, the input for occupancy schedule is given as '*off*' for the simulation period.
- The ISHRAE weather data file of the test site was customized for the simulation period using a open-source tool called '*Elements*' and the resultant output file was taken as input weather data file for simulation.
- Window openings are modelled as partial glass and partial PVC as per the actual sizes. Thermal, visible and solar properties of single-glaze glass are taken as given in the in-built property library of the software while for PVC, the following are the values of the properties given as input [3,4]:
  a) Thermal conductivity = 0.19 W/m-K
  b) Outside solar reflectance = 0.8
- To model the recessed window of the bedroom in the simulation tool, a '*reveal outside depth*' of 0.53m (as per the drawing) is given as an input.
- Thermophysical properties of the walling material (AAC) was taken from the in-built property library of the simulation software.
- To model the forced convection due to ceiling fan (28W) running continuously for the monitored period, the convective heat transfer coefficient for internal wall surfaces is taken as 15 W/m^2-K
- Natural ventilation through the flat (except WC & bathroom and corridor) is modelled by using the measured hourly air change (ACH) rate data.

RESULTS

Monitoring results

a) Indoor temperature

- Indoor temperature for the bedroom goes up to a maximum average of 32.7°C during the day and minimum average of 30.6°C early morning (**Figure-4**) . The maximum average ambient temperature was 39.3°C, while the average minimum ambient temperature was 27.8 ºC. Thus compared to the diurnal varaiation of 11.5 ºC in the ambient temperatures, the diurnal varaition in indoor temperature was only 2.1 ºC. For the present study, the Indian Model for Adaptive Comfort (IMAC) is chosen as the thermal comfort model [5,6]. As seen in **Figure**-4, all hours of the monitored period falls within the 80% acceptability limits whereas 87% of the monitored period falls within the 90% acceptability limits.

b) Air change rate

- Variation of carbon dioxide concentration inside the flat for a representative day is shown in **Figure-5**. The measured concentration of CO_2 was used to measure average air change rate (ACH) inside the flat using **Equation-1**.
- From the measured CO_2 data (corresponding to the duration of computer simulation), the average ACH calculated for the daytime (closed windows) was 6.8h^{-1} whereas for the nighttime (open windows) the average ACH was 23.41h^{-1}.
- The window design ensures an average ACH of 23h^{-1} when they are open, through natural ventilation itself, which indicates very good cooling potential. This is enabled by the good wind speed available on-site and the accessibility to this wind through the windows of this flat.

Simulation results

- **Figure-6** shows the comparison of the measured and simulated temperature data of the bedroom inside temperature. To check the congruity between the measured and simulated data, Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were calculated for the dataset [7]. The temperature data from the simulated model matched the measured temperature data very well with MBE = -0.09, RMSE = 0.7 and an absolute average deviation of 0.6°C.

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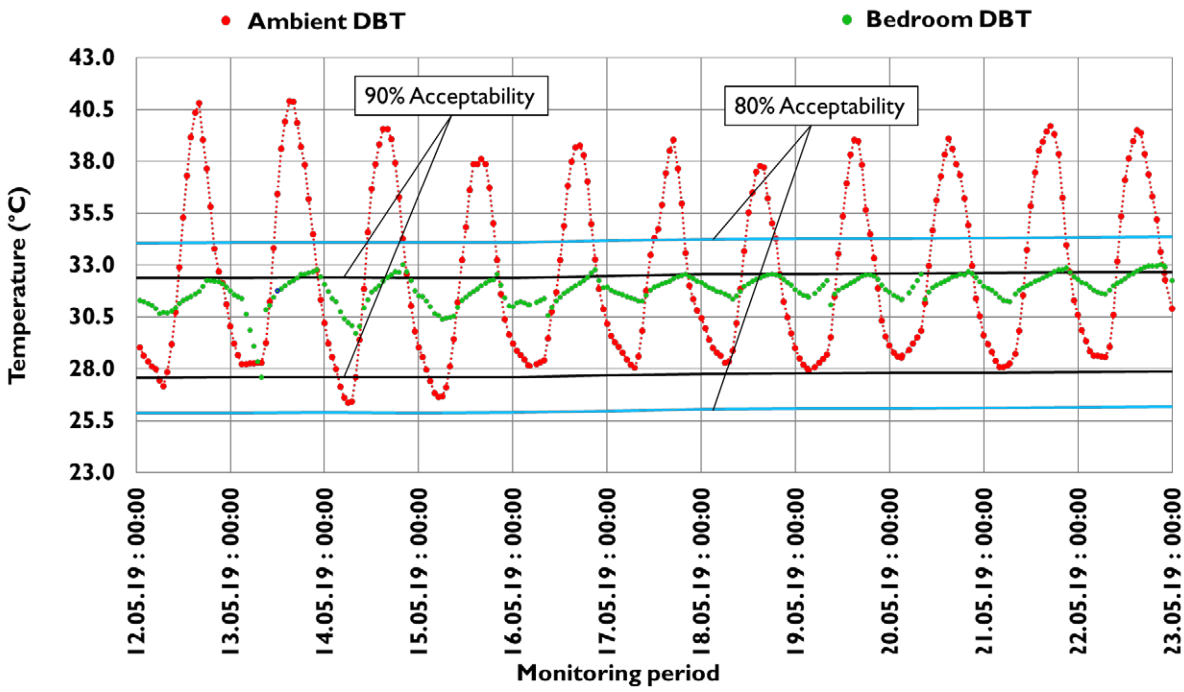

Figure 4: Graph showing monitored ambient temperature and temperatures inside the test flat (bedroom)

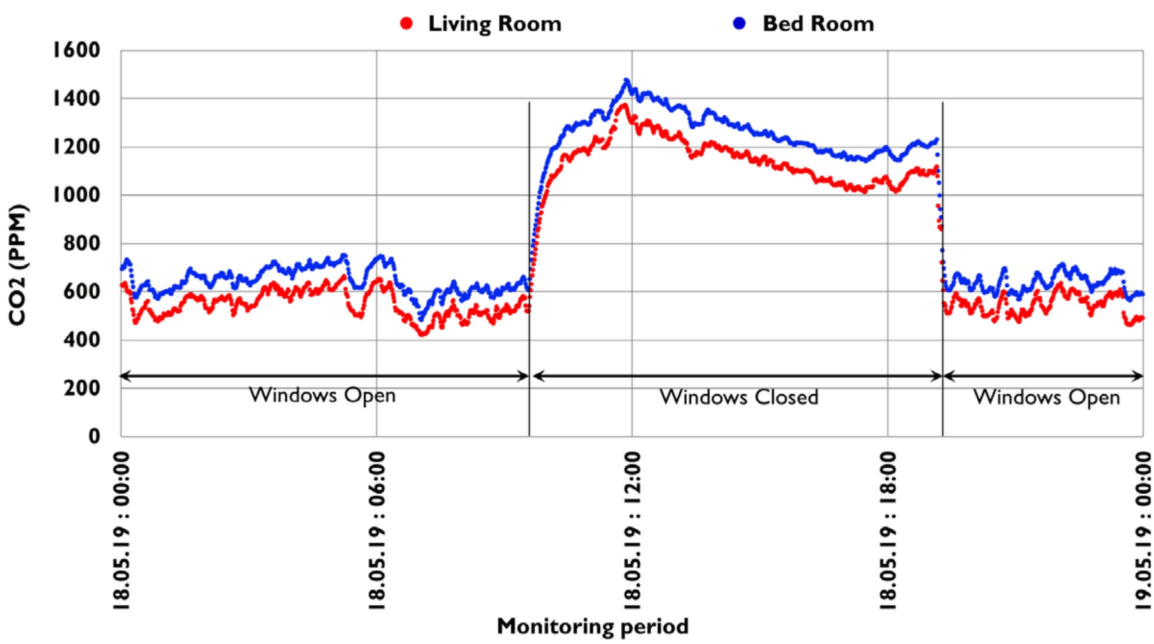

Figure 5: Graph showing monitored CO_2 concentration for a representative day inside the test flat (bedroom & living room)

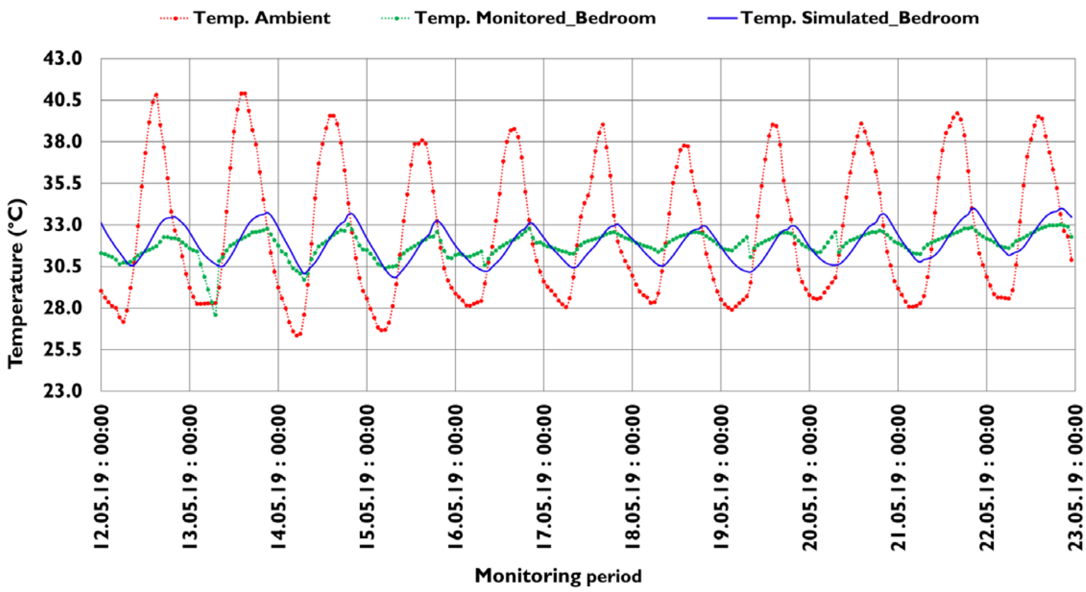

Figure 6: Graph showing comparison of measured and simulated bedroom inside temperature of the test flat.

CONCLUSIONS

The results of the monitoring show a quantifiable impact of building envelope (both construction material and openings for ventilation) on internal temperatures. It shows that with building envelope interventions it is possible to get maximum average temperature of 32°C in summer when the average maximum ambient temperature is 39°C, thus, increasing comfortable hours and reducing the need for air-conditioning.

The MBE and RMSE is calculated to be -0.09 and 0.7 respectively, which indicates a reasonably good match between the measured and simulated results.

NOMENCLATURE

DBT = Dry bulb temperature

NLPM = Normal litre per minute

RH = Relative humidity

ACH = Air change rate, h^{-1}

$\bar{Q}$ = Average air-flow rate or ventilation rate, m^3/h

Q_T = Instantaneous injection of CO_2 , m^3/h

C = Instantaneous CO_2 concentration, mol (CO_2)/ mol (air)

V = Volume of the space , m^3

t = Measurement period, h

ACKNOWLEDGEMENT

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CITY SPECIFIC DYNAMICS OF ENERGY, ENVIRONMENT AND COMFORT FOR ROOM AIR CONDITIONER PERFORMANCE

Nidhi Rai Jain[1], Rajan Rawal[1], Shubhashis Dey[2]

[1]*Faculty of Technology, CEPT University*
Ahmedabad, India
Nidhiraijain@gmail.com

[1]*Centre for Advanced Research in Building Science and Energy, CEPT University*
Ahmedabad, India
Rajanrawal@cept.ac.in

[2]*Shakti Sustainable Energy Foundation*
New Delhi, India
Shubhashis@shaktifoundation.in

ABSTRACT

Final energy use for cooling in buildings has tripled between 1990 and 2016 to 2020 terawatt hours. Excluding China and Japan, India accounts for about 28% of the Room Air Conditioner (RAC) market in Asia. RAC penetration is comparatively lower at 5% in India but raising with 12% CAGR growth. Use of RAC provides thermal comfort leading to better living standard, simultaneously use of energy and refrigerant to operate RAC impact environment. Seasonal Energy Efficiency Ratio (SEER) is the most used method to quantify the energy efficiency of RAC. The importance of comprehensive environment impact, accounting direct and indirect emissions by RAC will help mitigate environmental challenges. This paper adopts a methodology using ISO 16358-1 combined with hourly temperature bin to calculate Indian SEER (ISEER). Cooling Seasonal Energy Consumption (CSEC) is developed as a metric accounting different climate represented by cities and comfort models. Total Equivalent Warming Impact (TEWI) was used to account direct (refrigerants) and indirect (energy consumption) emissions. The study accounts for 12 Indian cities having high GDP growth, four RAC selected out of 282 RAC surveyed for the study. In comparison of ISEER mentioned by BEE, the study observes 9-20% higher ISEER in New Delhi and 9-16% lower in Bangalore. CSEC and TEWI are observed to be highest in Ahmedabad and lowest in Bangalore with a maximum difference of 2,520 kWh/year and 20,640 CO_2-eq respectively. For Delhi, CSEC was observed at 23% lower with adaptive comfort model for AC operation building then static comfort model. The contribution of direct emissions to TEWI was observed 10-20% with R410a and 4-8% with R32.

Keywords— RAC, ISEER, Comfort, Energy efficiency, Environment

INTRODUCTION

The global energy use in buildings has increased by 20% between 2000 and 2017. Buildings and appliances contribute to 30% of global energy use (IEA, 2018b). In India, the energy demand for building sector will grow more than five times by the end of the 21st century (Chaturvedi and Shukla, 2014). The energy performance of India's building sector has a critical impact on the climate. The conversion to low-carbon measures can contribute toward the goal of limiting global warming to below 2° C (Graham and Rawal, 2018).

The energy consumption and CO_2 emissions could increase to 700% by 2050 in the event of any inaction to achieve energy efficiency, compared to 2005 levels (GBPN, 2014). India accounts for about 28% of the Room Air Conditioner (RAC) market in Asia (excluding China & Japan) and 4% approximately of the global market. India have experienced rapid growth of split type RAC sales mostly attributed to demand from residential sector. Against 4.5 million RAC in 2017, India is expected to see 7.7 million RAC in 2020 as estimated (CLASP, 2017).

A combined approach to reduce carbon from the energy sector and improving the energy efficiency of space cooling could reduce cooling energy-related GHG emissions to 7% levels by 2050 as compared to baseline 2016 levels (IEA, 2018a). In India, total final energy demand is projected to grow from 9 x 1015 kJ in 2014 to more than 14 x 1015 kJ in 2050 in the absence of any mitigation actions. Such actions needs a change of refrigerant and improvements in system design efficiency (Graham and Rawal, 2018). Increase in energy production using fossil fuels has an adverse effect on climate, also the refrigerant released during the lifetime of the system has a huge contribution to climate change. Use of any appliance relying on electricity and refrigerant leads to direct and indirect emissions. The refrigerant used in cooling equipment releases HFCs which is one of the causes of global warming. The Kigali Amendment has added HFCs to the controlled substances under the Montreal Protocol (IEA, 2017). Improving the energy efficiency of RAC simultaneously adopting low GWP refrigerants will be a crucial step to reduce the energy consumption, peak load and emissions impacts of the equipment (Shah, Park and Gerke, 2017).

Residential buildings account for more than 70% of total final energy consumption in building globally in 2017, mostly influenced by population & floor area (IEA, 2018a). The long-term goal of reducing the energy use for cooling can also be achieved by improving cooling thermal comfort and reducing the need for space cooling (IEA, 2017). Following literature review is structured to provide an over view of work carried out in (i) Impact of increase RAC design efficiency (ii) Impact of RAC on operational energy consumption and (iii) Use of refrigerant in RAC and its impact.

Air conditioning was conceptualized in the beginning of the 20th century for industrial and commercial purposes (Cooper, 1998). Biddle, (2008) has carefully documented that rise in income and decline in electricity rates during the 1960s caused penetration of residential air conditioning. According to a survey conducted in 1959, 86% of people reported preferences for homes with air-conditioner over one without it (Ackermann, 2002). The prime reason for penetration of residential air conditioning systems was to keep cool in hot season and increasing incomes boosted its use.

Along with production of RAC having higher energy efficiency and low GWP refrigerant, use of the RAC also play critical role in reducing negative environment impact. Two occupant thermal comfort models are in practice driving operational energy due to RAC. The need to define acceptable indoor temperatures led to the study of thermal comfort and introduction of thermal comfort indices (Fanger, 1970); (Nicol, Humphreys and Roaf, 2016). Initially, static temperatures were prescribed for thermal comfort but in recent time the adaptive thermal comfort model has gained wider acceptability (Dear, Brager and Cooper, 1998). Indian National Building Code 2016 (Bureau of Indian Standards, 2016) and Energy Conservation Building Code 2017 (Bureau of Energy Efficiency, 2017) recommends India specific thermal comfort model (Manu *et al.*, 2015). Kumar et al., (2018) and his team conducted a nationwide survey and found that 66% of the population operates RAC along with use of any airmotion device such as ceiling fan. This establishes the need to retain adaptability and user preferences while devising guidelines and codes.

Energy efficiency rating for RAC in India have been determined by the Bureau of Energy Efficiency (BEE) and been expressed as labels with stars. BEE adopted the ISO 16358 standard in 2015 with a modified temperature bin distribution above 24° to 43°C (Shah *et al.*, 2016). The same temperature bin distribution is used to determine Indian Seasonal Energy Efficiency Ratio (ISEER) across the country despite regional variation in climatic conditions. The ISEER was developed for both fixed speed RACs and inverter RACs by BEE. ISO 16358-1 standard was referred for ISEER calculations for the study presented in this paper. A market status report (AEEE, 2015) observes that while occupants understand the relevance of energy efficient system, but do not practice to achieve energy savings during use of RAC. The report also refers the economic payback period as a barrier. The study observes that BEE estimates energy savings in kWh for a cooling system with the reference use of 1600 hours per year (Ministry of Power, 2017). However, as study points out that the actual use of the RAC is more than 1600 hours, there is a need to consider a total number of hours above 24°C for which cooling is required.

Shah et al., (2017), concluded that efficiency of RACs degrade with increased ambient air temperatures irrespective of use of refrigerants. The study included refrigerants such as R-410A, R-32, and R-290. Wu et al., (2019) studied the tolerance value for energy efficiency of RACs using alternative refrigerants as shown in Table 1. The study states that the prime objective of improving RAC standards is to reduce its environmental impact. Therefore, the total emissions should also be studied.

	R410A	**R32**	**R290**
GWP	2088	675	6
$SEER_{upper}$	4.60	4.26	4.10
$SEER_{lower}$	4.10	3.76	3.60
Difference	0.5	0.5	0.5

Table 1:Comparison between Linear function of SEER and GWP for RAC. This lists the refrigerants available for RACs in India.

Kumar, Sachar, Kachhawa, Goenka, et al., (2018) projected a savings potential of 19% for annual energy consumption leading to 25% in total carbon emissions by RACs in 2027. This includes a 10% reduction in RAC run-time installed in energy-efficient buildings and in event of adaptive thermal comfort strategies, the study emphasis the need to focus on total emissions along with improvement in efficiency.

Makhnatch & Khodabandeh, (2014) have studied three environmental metrics namely Total Equivalent

Warming Impact (TEWI), Life Cycle Climate Performance (LCCP) and Global Warming Potential (GWP). They investigated uncertainties in use of there metrics. Their study reveals that TEWI is a simpler metric to use than LCCP metric and at the same time more correct than GWP while selecting refrigerant. They have also stated that TEWI is a better metric to evaluate the environmental impact as compared to GWP as it accounts for energy efficiency of the system. Later, Makhnatch, Mota-Babiloni, López-Belchí, & Khodabandeh, (2019) conducted an experimental setup to compare the performance of lower GWP refrigerants and carried out the TEWI metric based analysis for a refrigeration unit with a designed cooling capacity of 1.83 kW. For, all the cases studied by the authors for the refrigearnts such as R134a, R450A and R513A, results suggested that the direct emissions were low due to reduced refrigerant leakage. The impact of leakage and recovery losses was reduced with lower GWP refrigerants. The larger part of the environmental impact was because of the energy efficiency variation between refrigerants.

TEWI is a measure used to evaluate the global warming impact of equipment based on indirect emissions during the operation of the equipment and the direct emissions due to disposal of the operating fluids (Makhnatch and Khodabandeh, 2014). It is measured in a unit of mass in kg of carbon dioxide equivalent (CO_2-e). It highlights that the largest impact of global warming from air conditioning is through electricity consumption leading to indirect emissions. The Australian Institute of Refrigeration Air Conditioning and Heating, (2012) has mentioned few limitations of TEWI calculations due to its dependence on assumptions considering equipment performance & use patterns, refrigerant properties and electricity generation efficiencies. But it also recognises the insignificance of small differences in TEWI.

Another study by Goetzler, et al., (2016) points towards the need to focus on reducing annual space cooling demand (kWh) as it contributes majorly to the indirect emissions. The study attempted to understand the trends in global air conditioning market with reference to direct and indirect emissions. Considering the life span of RACs, its carbon footprint is dominated by indirect emissions. This is because the carbon intensity of fossil fuels used for electricity generation is high. The aim of this study is to develop a correlation between indoor comfort temperature, the energy efficiency of RACs and total carbon emissions (direct & indirect) considering the life span of RACs. This information can be useful to manufacturers who aim to design energy efficient systems with low GWP refrigerant. This study can also help in predicting annual energy use by a RAC at city-level.

The study includes two refrigerants (R410a & R32) which is dominant in the Indian market for RACs. The study focuses only on dry bulb temperature for indoor & outdoor conditions as a parameter for comfort and excludes wet bulb temperature. This study calculates and evaluates indirect carbon emissions based on emission factors identified in accordance with the relevant Clean Development Mechanism (CDM). The database includes all grid-connected power stations which use non-renewable energy sources.

METHODOLOGY

The following narrative contains the methodology adopted for this study. The methodology is derived based on the literature review and investigated appropriateness of metrics that could help to define the relationship between energy efficiency, comfort and environment impact of RACs in India. 12 tier- I cities in India were selected based on the highest projected population and projected GDP by 2030 (McKinsey Global Institute, 2010). During selection of the cities equal emphasis was given for climate zone representation. Climate classification prescribed as ECBC 2017 was taken as reference. The summary of findings across these 12 Indian cities is presented in Table 2. Typical Meteorological Year (TMY) weather data files (2003-17) developed by Climate.onebuilding.org is used for this study.

LOCA-TION	POPULATION IN 2030 (MILLION)	GDP, 2030 ($ BILLION)	CLIMATE TYPE
Mumbai	33.0	265	Warm & humid
New Delhi	25.9	296	Composite
Kolkata	22.9	169	Warm & humid
Chennai	11.0	73	Warm & humid
Bangalore	10.1	127	Temperate
Pune	10.0	76	Warm & humid
Hyderabad	9.8	67	Composite
Ahmedabad	8.4	68	Hot & Dry
Surat	7.4	53	Hot & Dry
Jaipur	5.4	24	Composite
Nagpur	5.2	37	Composite
Kanpur (Lucknow)*	4.2	15	Composite

Table 2: List of Selected locations in India with population, GDP, and Climate type

*(*Note: TMY weather file was not available for Kanpur, Lucknow weather file was used as per surrogate city finder method* (Garg *et al.*, 2015). *Therefore, results are presented for Lucknow hereafter.)*

(TERI, NRDC and IGSD, 2018) conducted a study on estimated room ACs in India by refrigerant. The results indicated 70%, 17%, 11% and 2% of market share by R22, R32, R410A and R290 respectively in 2 to 5 star ACs. A market survey was conducted for this study which includes the capacities, refrigerant used and ISEER rating of RACs available in India. It includes list of 282 split ACs from 8 leading manufacturers in India. The number of available split type systems using refrigerant R410a were found to be dominant in comparison with R32 and R290. Our previous study states that even though R290 is the lowest GWP refrigerant compared to the other two, there was only 2% of products available out of 282. More than half of the products were having a capacity of 1.4 TR (6.6 HP) or more (Jain and Rawal, 2019). Findings of the market survey were set as the selection criteria for the RACs.

The calculations were not possible with the data limited of refrigerant type, rated capacity and ISEER/EER ratings of available RACs. Therefore, to derive performance details of RACs at various outdoor DBT, a software named Coolselector2 version 3.1.2 developed by Danfoss was used. This software enables to select best-suited component based on various parameters such as cooling capacity, refrigerant, evaporation & condensation temperature, and other critical variables for refrigerant systems. It features calculations based on user's requirements or standard operating conditions. Since most of the system curves are not available in a form to be used for detailed calculation the authors relied on four systems for which required information is available. The authors do not claim to represent all 282 surveyed systems by selecting only four systems. Two systems were selected from Coolselector2 and two units systems from a reference study done by Kumar et al. (2018) and team. The laboratory test results for the selected units with inverter technology was used to calculate seasonal energy performance. Further details of the selected systems are listed in Table 3.

	REFRIGERANT	CAPACITY	ENERGY PERFORMANCE
Case 1	R410-A	1.5 TR	3.65 (EER)
Case 2	R32	1.5 TR	5.20 (ISEER)
Case 3	R410-A	2.0 TR	3.75 (COP)
Case 4	R410-A	2.0 TR	3.88 (COP)

Table 3:Comparison between Linear function of SEER and GWP for RAC

Calculations:

As specified by Bureau of Energy Efficiency (BEE), reference outdoor temperature bin hours have been calculated for eight months from 1st March to 31st October. The reference outdoor temperature bin distribution range has been modified by the BEE to 24° C to 43° C for Indian climate conditions as mentioned in IS1391:1992 (Part I and II).

The process for calculating the cooling seasonal load, cooling seasonal energy consumption (CSEC) and ISEER is in accordance with International Standard ISO 16358-1 as mentioned by BEE. The calculation procedure is given for 4 types of capacity units in ISO 16358-1. It was inferred from the market survey that RACs with inverter technology available in India are rated for 100% capacity and 50% capacity only. Therefore, procedure given for multistage capacity units were used in this study.

Cooling Seasonal Performance Factor (F_{CSP}) is specified in ISO 16358-1 which is also known as ISEER for products available in the Indian market. Cooling seasonal performance factor (F_{CSP}) is the ratio of Cooling seasonal total load (L_{CST}) and Cooling seasonal energy consumption (C_{CSE}). The unit for both L_{CST} and C_{CSE} is watt-hour (Wh). Therefore, the CSPF or ISEER value is unitless and is calculated using Equation 1.

In equation 2, LC (t_j) is defined cooling load, and F_{ful} (t_j) is capacity characteristics against outdoor temperature. Defined cooling load was calculated for temperature conditions t_0 = 23° C and t_{100} = 43° C as per modified temperature bin calculation for India. In equation 3, X (t_j) is operation factor, P_{haf} (t_j) is cooling half power input at outdoor temperature, F_{PL} (t_j) is Part load factor, P_{hf} (t_j) is third stage cyclic operation, P_{ful} (t_j) is power input against outdoor temperature.

Equation 4 was used to calculate the total environmental impact by a refrigeration system (The Australian Institute of Refrigeration Air Conditioning and Heating 2012). GWP is Global Warming Potential of refrigerant, L_{annual} is Leakage rate p.a. (kg), n is system operating life (years), m is refrigerant charge (kg), $\alpha_{recovery}$ is recovery/ recycling factor from 0 to 1, E_{annual} is energy consumption per year (kWh p.a.), and ß is indirect emission factor (kg CO_2 per kWh). Leakage rate, refrigerant charge, and recovery factor are system specific and depends on the installation of the system. Thus, these parameters are considered same for all the calculations for justified comparison including system operating life. Literature suggests that the major impacting factor is annual energy consumption for cooling, which is dependent on the seasonal energy efficiency of the system and annual cooling hours of the city.

$$F_{CSP} = \frac{L_{CST}}{C_{CSE}} \quad [1]$$

$$L_C(t_j) = \phi_{ful}(t_{100}) \times \frac{t_j - t_0}{t_{100} - t_0} \quad [2]$$

$$\phi_{ful}(t_j) = \phi_{ful}(43) + \frac{\phi_{ful}(34) - \phi_{ful}(43)}{43 - 34} \times (43 - t_j) \quad [3]$$

$$TEWI = GWP\ (direct; refrigerant\ leaks\ incl. EOL) + GWP\ (indirect; operation) = (GWP * m * L_{annual} * n) + (GWP * m * (1 - \propto_{recovery})) + (E_{annual} * \beta * n) \quad [4]$$

$$Indoor\ operative\ temperature = (0.078\ X\ outdoor\ temperature) + 23.25 \quad [5]$$

$$Indoor\ operative\ temperature = (0.28\ X\ outdoor\ temperature) + 17.87 \quad [6]$$

Based on thermal comfort model, we used terminology called 'static indoor setpoint' for static thermal comfort model and 'Adaptive setpoint' for adaptive thermal comfort mode. The adaptive thermal setpoint account for outdoor temperature. Therefore, variable indoor setpoint with reference to outdoor temperatures ranging from 24° C to 43° C is calculated for a city. This was done using Equation 5 for air-conditioned and Eqauation 6 for mixed mode buildings as mentioned in NBC 2016. This method is adopted to determine indoor conditions for fully air-conditioned buildings. Indoor operative temperature (in °C) is neutral temperature and outdoor temperature is the 30-day outdoor running mean air temperature (in °C). The 90% acceptability range for the adaptive models for AC buildings is ± 1.5° C and for MM buildings is ± 3.46° C.

The adaptive indoor setpoints were calculated for a city using above equations. For static setpoints, t_0 is considered as 23° C and for adaptive setpoints, t_0 will vary for each outdoor temperature bin. Thus, the Defined cooling load L_C (tj) is calculated with variable adaptive setpoint (t_0) with reference to each outdoor temperature bin t_j using Equation 2. The calculations for CSPF, CSEC and TEWI will be the same as mentioned above.

RESULTS & DISCUSSIONS

The calculation methods mentioned above was used to evaluate the performance of RACs. The comparative results and observations mentioned below are specific for 12 selected Indian cities and 4 selected RACs. This was done to validate the proposed methodology which can be used for future work with more systems and more cities.

The ISEER results as per BEE method and proposed methodology were compared among12 cities. In Figure 1, for all the four cases, the ISEER value mentioned by BEE is closest to Hyderabad and Kolkata as per proposed methodology. It is observed to be highest in New Delhi and lowest in Bangalore city for all cases. In New Delhi, Ahmedabad, Lucknow, Jaipur, Chennai and Nagpur the calculated value of ISEER is more than the ISEER mentioned by BEE. In Pune, Surat, Mumbai and Bangalore it is calculated lower than BEE. As per literature review, it was inferred that the variation in ISEER will affect the CSEC and TEWI score. Higher the ISEER (energy efficiency) value lower will be the CSEC (kWh) and therefore lower TEWI. To investigate it further CSEC was compared for 4 RACs in all 12 cities.

In Figure 2, it is observed that CSEC of all RACs is lowest in Bangalore and highest in Ahmedabad. Although the highest ISEER is calculated in New Delhi city, lowest CSEC (kWh) is calculated in Bangalore with lowest ISEER value in all 4 cases. The trend observed in CSEC of 4 RACs is same in all 12 cities. As mentioned in literature improving ISEER values will lead to maximum energy savings. The above results show that ISEER alone is not effective to predict CSEC. BEE estimates CSEC for a RAC with the reference use of 1600 hours per year. This study estimates the CSEC for total number of hours above 24°C for which cooling is required in different cities using weather data file.

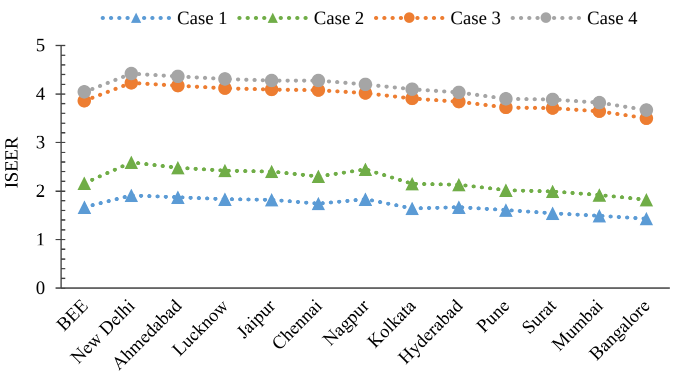

Figure 1: Comparison of ISEER of 4 RACs in 12 cities

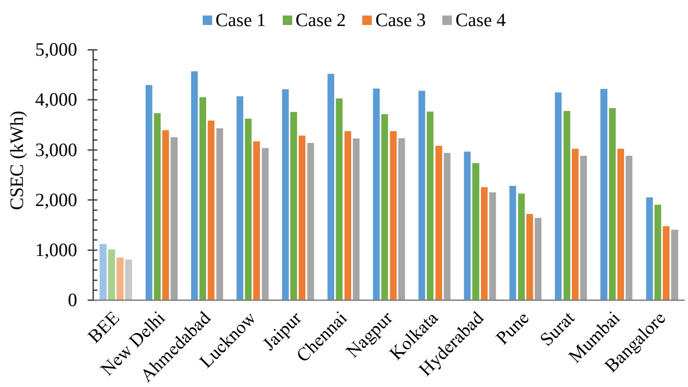

Figure 2: Comparison of CSEC of 4 RACs in 12 cities

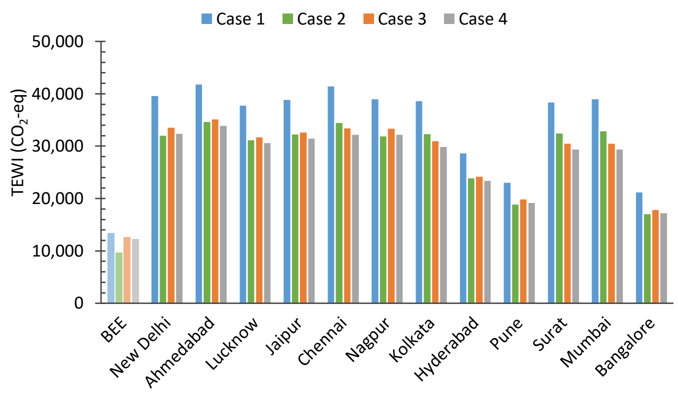

Figure 3: Comparison of TEWI for 4 RACs in 12 cities

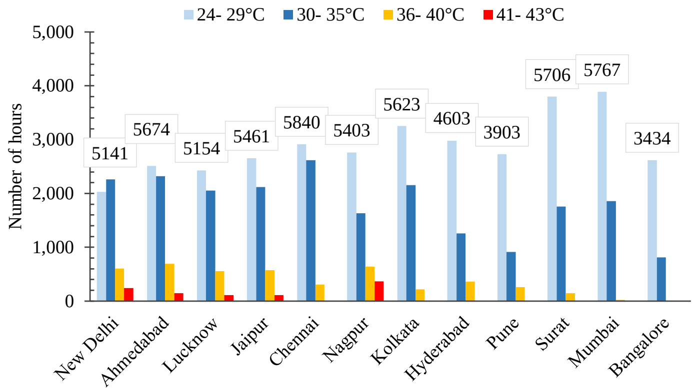

Figure 4: Comparison of outdoor temperature bin hours distribution and total for each city

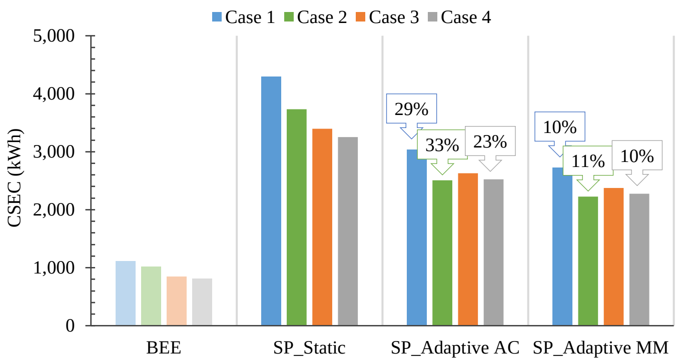

Figure 5: Comparison of CSEC with static and adaptive setpoints for RACs in New Delhi

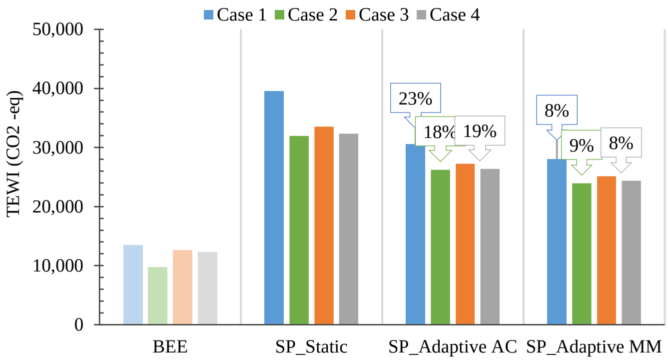

Figure 6: Comparison of TEWI with static and adaptive setpoints for RACs in New Delhi

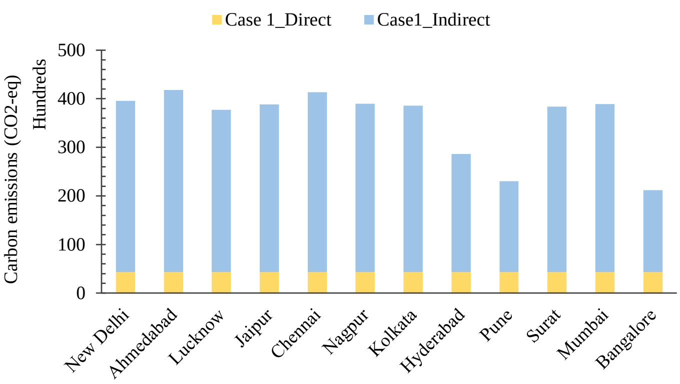

Figure 7 (a): Comparison of direct and indirect emissions of Case 1 in 12 cities

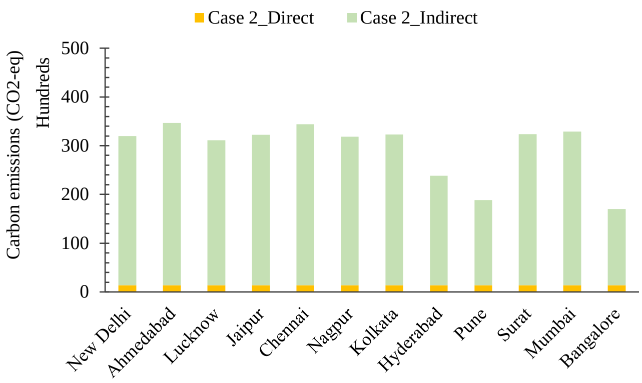

Figure 7 (b): Comparison of direct and indirect emissions of Case 2 in 12 cities

In Figure 3, it is observed that TEWI of all RACs is lowest in Bangalore and highest in Ahmedabad, like CSEC. The trend observed in carbon emissions is same as CSEC for all 4 RACs in all 12 cities. This is because CSEC (kWh) dominates in TEWI calculations as all the other variables are kept constant. Please note that BEE doesn't calculate TEWI score, it was done in this study for comparison. As mentioned in literature improving the energy efficiency of RACs will lead to reduction in energy use and carbon emission (Shah, Park and Gerke, 2017). In some cases, the above observation is contradictory to the literature that higher ISEER systems will have lower CSEC and carbon emissions (TEWI). This observation leads to investigate the city climate further with the outdoor temperature bin hours of the cities.

In Figure 4, it is observed that all the cities experience more than 80% of the bin hours within medium temperature conditions. The 5 cities New Delhi, Ahmedabad, Lucknow, Jaipur and Nagpur experience less than 13% of the total bin hours above 36° C, which is high and extreme temperature conditions. It results in higher peak energy demand in the above cities (Note: It is evaluated based on dry bulb temperature only. It doesn't account for wet bulb temperature and latent load). The total of temperature bin hours is maximum in Chennai followed by Mumbai and Surat, but the outdoor temperature is below 35° C for 95% of the total bin hours. The total of temperature hours is minimum in Bangalore; thus, it has minimum CSEC (kWh) even with lowest ISEER value. It is worth noting that although a system with higher efficiency i.e. ISEER leads to lower CSEC when compared in one city. But, when the performance of a single system is compared within 12 cities, the outdoor conditions play an important role in calculation of CSEC (kWh) and TEWI. This leads to an important observation that CSEC (kWh) and TEWI can significantly be reduced with an adoption of adaptive setpoints in RACs. Therefore, to study the expected savings, the CSEC (kWh) and TEWI using adaptive setpoints was calculated.

In Figure 5, the CSEC (kWh) of Case 1 can be reduced to 29% and 10% more by adopting adaptive setpoints for AC and MM building respectively as compared to static SP. In Case 2, the CSEC (kWh) can be reduced to 33% using adaptive SP for AC and 11% more with adaptive SP for MM building as compared to static SP. For Case 3 & Case 4, the savings calculated in CSEC is 23% using adaptive SP for AC and 10% more using adaptive SP for MM as compared to static SP.

In Figure 6, the carbon emissions defined by TEWI of Case 1 can be reduced to 23% and 8% more by adopting adaptive setpoints for AC and MM building respectively as compared to static SP. In Case 2, the TEWI can be reduced to 18% using adaptive SP for AC and 9% more with adaptive SP for MM as compared to static SP. For Case 3 & Case 4, the savings calculated in CSEC is 19% using adaptive SP for AC and 8% more using adaptive SP for MM as compared to static SP. The above calculations are done for New Delhi with different setpoints for static, AC and MM conditions. Similarly, the CSEC and TEWI can be calculated for all the cities using above method.

As mentioned in the literature improving energy efficiency of RAC while shifting towards low GWP refrigerants will lead to lower energy consumption and emissions impact of the system. Thus, it was important to investigate the contribution of direct (refrigerant) and indirect emissions (kWh) in total carbon emissions from above results. The carbon emissions from two systems Case 1 with R410a and Case 2 with R32 were compared in 12 cities.

In Figure 7 (a), Case 1 uses refrigerant (R410a) with higher GWP of 2088 and therefore it contributes to 10% to total carbon emissions in Ahmedabad & Chennai. The contribution of direct emissions in Bangalore is 20% to total carbon emissions with same system. This is important to note that direct emissions from the system is same in all cities, but due to the change in indirect emissions the percentage contribution increases.

In Figure 7 (b), Case 2 uses refrigerant (R32) with lower GWP of 675 and therefore its contribution is less as compared to Case 1 in total emissions. The minimum percentage contribution is 4% in seven cities and maximum 8% in Bangalore for Case 2. Thus, to reduce total environment impact it suggests focussing more on CSEC (kWh) which contributes to indirect emissions than low GWP refrigerants.

CONCLUSIONS

This study was carried out to evaluate the variation between existing ISEER calculations as mentioned in the BEE rating system. This study has helped in identifying the factors effecting Cooling Seasonal Energy Consumption (CSEC) and carbon emissions defined by TEWI score for RACs. This study also develops a method to calculate ISEER beyond BEE standard method and propose CSEC as a metric for various cities and various comfort models using indoor setpoints. Further, CSEC is used to quantify the contribution of indirect emissions in total carbon emissions.

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The results were obtained for 4 RACs and their performance is compared with 12 Indian cities using proposed methodology. With this limited scope of the study the major findings are:

- The existing ISEER calculations mentioned in the BEE rating system doesn't account for the variations in outdoor temperature bin hours across the country. Therefore, ISEER value mentioned by BEE is not helpful in determining the CSEC for a system.
- The outdoor temperature conditions were found to be an important factor in calculations of CSEC (kWh) and total carbon emissions (TEWI) when the performance of RACs was compared in 12 cities.
- The calculations were also done for ISEER, CSEC and TEWI using adaptive indoor setpoint temperature in New Delhi. Approximately 30% savings in CSEC (kWh) were predicted in New Delhi for all the 4 cases of RACs. This leads to approximately 20% savings in carbon emissions (TEWI) just by adopting adaptive setpoints for AC as determined by IMAC method.
- The contribution of direct emissions (refrigerant) in total carbon emissions was found to be less than 20% with higher GWP refrigerant and less than 8% with lower GWP refrigerant. The direct emissions were constant in all cities, the variations observed was because of indirect emissions (kWh). Thus, there is need to focus more on CSEC (kWh) than low GWP refrigerant to reduce total carbon emissions which causes rise in temperatures and leads to climate change.

FUTURE SCOPE

In future authors wishes to develop a single equation to define the relationship between climate, indoor setpoint temperatures, and the total environmental warming impact.

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NOMENCLATURE

DBT	= Dry- bulb Temperature
EUI	= Energy Use Intensity
GDP	= Gross Domestic Product
GHG	= Green House Gases
ISO	= International Organization of Standardization
k, p, n, m	= number of temperature bins
nj	= bin hours
t	= general continuous outdoor temperature
tj	= outdoor temperature corresponding to each temperature bin

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TECHNICAL POTENTIAL OF INTEGRATING EVAPORATIVE COOLING SYSTEM WITH MECHANICAL COOLING SYSTEM IN HOT & DRY CLIMATE FOR DAY USE OFFICE BUILDING IN INDIA

Bipinchandra Patel[1], Rashmin Damle[2], Maaz Dixit[1]

[1] *Neev Energy and Sustainable Solutions*
Ahmedabad, India
bipin@neevenergy.co
maaz@neevenergy.co

[2] *CEPT University*
Ahmedabad, India
rashmin.damle@cept.ac.in

ABSTRACT

In hot and dry regions of India, there are significant economic and environmental benefits of using an integrated system that incorporates evaporative cooling and conventional meachanical cooling systems. The aim of this work is to study the technical potential resulting from the integration of direct evaporative cooling with a mechanical cooling system. The scope of this work is limited for the small day-use office space in the hot and dry climate of India. This study focuses on an office space in Ahmadabad for which access and architectural & air-conditioning drawings and system details were available. Reference case model was created with certain approprieate changes to the envelope, shading, operating schedule, ventilation rate etc.with variable refrigerant flow (VRF) cooling system. Simulations are carried out to explore the effect of combining mechanical cooling with and without direct evaporative cooling (DEC). Ideal evaporative air flow rates to meet the cooling loads for the integrated system are found out. The study elaborates on the technical integration of the evaporative cooling system and direct expansion (DX) cooling systems. It further highlights the comfort conditions resulting from the use of an integrated system. The study also focusses on the energy consumption, thermal comfort and environmental benefits, limitations, and consequences of an integrated system.

Keywords—evaporative cooling system, mechanical cooling system, energy savings, HVAC EPI

INTRODUCTION

India is witnessing 5-6% increase in commercial floor spaces from the year 2010 (660 million m^2) and this trend is likely to continue till 2030 (1930 million m^2) (Kumar et al., 2010). For India, 66% of the buildings are yet to be built. Proposed Delhi- Mumbai industrial corridor (DMIC) passes through the states of Rajasthan, Gujarat and Maharashtra and is going to witness tremendous industrial and economic growth. Most part of this corridor falls in hot and dry climate zone of India.

At present in India, cooling energy usage is around 31% of the total energy usage in a typical commercial building (Manu et al., 2016). Increase in floor space and cooling power requirements put additional burden on existing energy infrastructure. Hot and dry climate & hot and humid climate makes the situation worse in most parts of India. Frequent load shedding and power grid failure in summer are common in many states of India (Abrar, 2016). In this situation, a reduction in cooling energy usage is a primary concern.

Fortunately, a lot of work is being done in areas of cooling system efficiency, envelope characteristics, building management systems, etc. A lot of theoretical and practical work has been carried out on low energy cooling solutions. One of the low-energy cooling techniques is evaporative cooling (Direct & Indirect). This is largely due to high latent heat of vaporization of water which is 2260 kJ/kg (J.K.Jain, 2007). Thus, each kilogram of pure water has a potential to provide 628 Wh worth cooling with an evaporative cooler.

It is estimated that up to 60-80% reduction in cooling energy consumption is possible with evaporative cooling in some cases (Porumb, BĂlan and Porumb, 2016). evaporative cooling technology can replce mechanical cooling in some cases. In open literature, integrated system of mechanical cooling and evaporative cooling have been explored in USA, UK, Romaniya and Australia. However, for these places, the highest summer temperature is around 29°C. (Vakiloroaya *et al.*, 2011), (Hernandez, Gas and Company, 1994), (B. Eric Lee, 2007). It should be noted that integrated system, also known as hybrid system performs differently at the same part-load capacity and efficiency as conventional DX systems (California Utilities Statewide Codes and Standards Team, 2013). Highest dry bulb temperature (DBT) for Ahmadabad is about 44°C when Relative Humidity is 38% and Wet Bulb Temperature is 24.4°C). With 90% effective evaporative cooler, indoor temperature can be brought down to 26.4°C only. In such a harsh climate, it is not always possible to have a year-round performance with a DEC alone. In the open literature, integrated system for office cooling in hot and dry (H&D) climate like that of Ahmadabad has not received much attention.

The intent of this simulation-based study is to identify the potential of integrating direct evaporative cooling and mechanical cooling systems. The study follows a step- by- step procedure to evaluate the mechanical and evaporative cooling system size, annual cooling energy and peak power requirements. Simultaneously this work also analyses resulting indoor environment in terms of dry bulb temperature (DBT) and relative humidity (RH) for cooling with mechanical cooling (VRF), cooling with direct evaporative cooling (DEC) and cooling with an integrated system of mechanical cooling and direct evaporative cooling. It also deals with limitations of running DEC in monsoon months and early mornings of winter months. The study is limited to day use office space and with DEC type evaporative cooling system only. A lot more work can be carried out to practically validate the results, study effect of different flow rates in different months & during different hours of the day and consequences of higher relative humidity (RH) on office interior and human health.

METHODOLOGY

Following are the different stages to find technical potential, through simulation, resulting from the integration of (DEC) with mechanical cooling systems.

Selection Criteria of an Office Space

Firstly, the envelope characteristics, space use and various internal loads for office space were understood. For this, an office space (194 m^2carpet area) was selected in Ahmadabad based on proximity, physical access and access to drawings and utility data. The office is in the south-east corner of the first floor of an office building, with longer façade facing east and west as shown in Figure 1.

There are air-conditioned offices on the north and west sides and in the floors above and below. Hence, for these surfaces, adiabatic adjacency is assumed. This office is cooled by a 40 kW VRF system. For

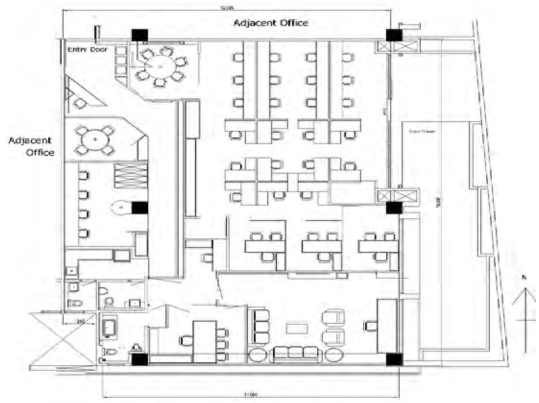

Figure 1 Office plan

simplicity, the office is divided into three thermal zones: open office, reception, and cabins zone based on orientation, adjacency and occupancy. The simulations were carried out with the DesignBuilder software (Design Builder Software Limited, 2016). Simulation results were recorded for (1) End use energy components (lighting, equipment, ventilation and cooling) and (2) Resulting indoor conditions in terms of unmet hours, dry bulb temperature, and relative Humidity.

Cases for Analysis

The following cases were modelled for an integrated solution of DEC:

- Base Case with lighting, equipment and ventilation system: LEV
- Reference case with mechanical cooling: LEVC
- Direct Evaporative cooling: LEV + DEC
- Integrated cooling system: LEVC + DEC

The physical model and internal loads (lighting and equipment) remain the same for all the cases.

Base Case Modelling: LEV Case

Appropriate changes were made to the envelope, internal load, occupancy scheduleetc. to the selected office in Ahmadabad. Thus the Base case is a model with space lighting (L), office equipment (E) and minimum ventilation requirement (V) through an air handling unit (AHU) as shown in Figure 2. A minimum ventilation rate of 0.11 m^3/s is calculated

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based on ASHRAE Standard 62.1 (2.5 l/s * 22 people + 0.3 l/s * 194 m^2 area). There is not any cooling system for this case.

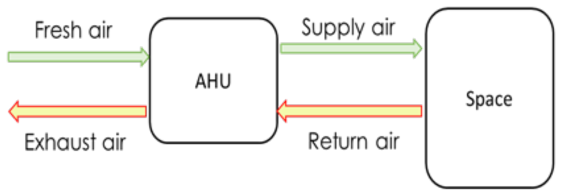

Figure 2 Schematic for Base case with light, equipment, and minimum ventilation

Cooling set point temperature (CSPT) of 25.5°C + 1.5°C tolerance is considered across all the cases. Thus, the highest acceptable indoor DBT limit is 27.0°C for calculation of cooling unmet hours in this study. Cooling set point temperature is on the conservative side. But methodology will remain the very same for any other CSPT and tolerance.

Simulation was carried out and results were recorded for important parameters like lighting load (L), equipment load (E) & Ventilation load (V) and Indoor environment parameters like unmet hours, DBT and RH.

Reference Case Modelling: LEVC

Reference case model is created by adding VRF type mechanical cooling system with co-efficient of performance (COP) of 3.71 (as found in the selected office), to have year-round cooling as shown in Figure 3. Since this case has lighting load (L), equipment load (E), ventilation load (V), and cooling load (C), it is called LEVC case. Since, the results of all other cases will be compared with the results of this case (LEVC), it is referred to as the Reference case.

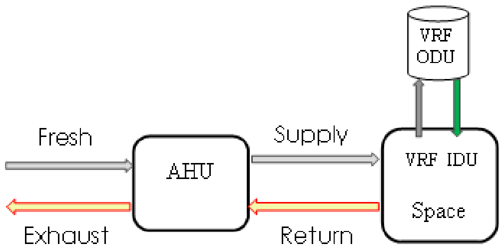

Figure 3 Reference case system layout

In this study, the VRF cooling system starts from 09:00 h, ie. one hour before office timing and stops at 19:00 h, except for Sundays. VRF cooling system size and indoor units (IDU) airflow rates were optimized such that VRF cooling system size is minimum and unmet hours in individual zones are similar and combined unmet hours for office are less than 300 hours as per Energy Conservation Building Code (ECBC) requirement. Numbers of simulations were carried out for this optimisation. A lower limit of 290 unmet hours is decided to make a narrow range of 290-300 hours to compare with other cooling solutions.

After optimised simulation, important results for energy and indoor environment are recorded. HVAC energy performance index (EPI), in this case, is 55.7 kWh/m^2-yr for minimum VRF coooling system size of 15.0 kW as found later during this study. High HVAC EPI and low RH conditions in dry summer period prompt to study cooling with DEC and integrated solutions.

Evaporative Case Modelling: LEV + DEC

In this case, DEC system is added to the Base case model such that fresh air pre-cooled by DEC is supplied to different zones through the AHU as shown in Figure 4. Various flow rates ranging from 0.11 m^3/s to 5.0 m^3/swere tested.

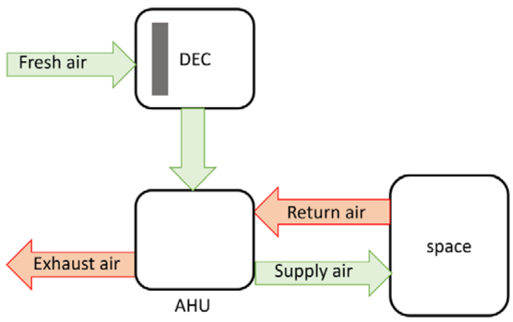

Figure 4 Schematic for evaporative case

Simulations were carried out and results are recorded for important energy and indoor parameters.High unmet hours of 1775 hours and continuous high RH conditions found later in this study prompt to work on integrated system.

Integrated Case: LEVC + DEC

In this case, DEC and VRF cooling systems, both are added to the Base case as shown in Figure 5. VRF cooling complements DEC cooling when DEC alone cannot provide required comfort as discussed earlier. Different DEC flow rates from 0.11 m^3/s to 5.0 m^3/s were simulated in different simulation runs.

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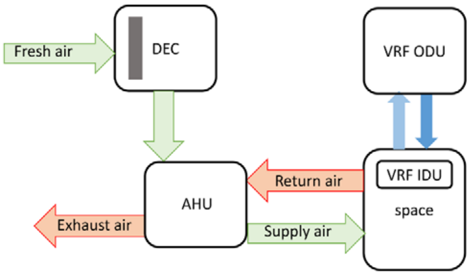

Figure 5 Schematic for Integrated Case

Ideal DEC flow rates are worked out considering (1) minimum energy criteria and (2) minimum unmet hours criteria. VRF system size is then optimised for maintaining unmet hours in the range of 290 to 300 for both criterion. Simulations results are recorded for important energy and indoor parameters. Furthermore, additional simulations were carried out to see the effect of DEC switching off to avoid (1) high humidity during humid months of July, August and September and (2) unnecessary cooling in the morning times of colder months of December, January and February.

RESULTS AND DISCUSSION

Lighting and equipment peak power and lighting and equipment annual energy consumption remains the same across all the simulation cases. Thus, only HVAC EPI and peak HVAC power are important to discuss. HVAC power and HVAC energy includes power or energy required for ventilation fans, VRF outdoor unit (ODU), VRF indoor units (IDU), AHU fans and for DEC fan as well as pump. Once the VRF flow rate and DEC flow rate are optimized, indoor environment conditions are similar within a very narrow range across all the three zones. Hence, discussions for DBT and RH are limited to open office zone as a representative zone which is largest in terms of floor area and occupancy also.The unmet hours and HVAC EPI are considered for the office as a combined space. Heating unmet hours are not the focus of this study and hence, only cooling unmet hours are discussed in this study.

Multiple cases with internal loads are simulated with mechanical cooling, DEC cooling or with integrated cooling systems. The combinations of different cases with their abbreviations and characteristics are shown below:

- LEV: Case with lighting, equipment and minimum ventilation air flow rate
- LEVC: Case with lighting, equipment, minimum ventilation and cooling with VRF system
- LEV + DEC (0.5 m^3/s): Case with lighting, equipment and ventilation through DEC with 0.5 m^3/sair flow rate
- LEVC + DEC (0.5 m^3/s, 15kW): Case with lighting, equipment, ventilation and cooling through DEC (0.5 m^3/s air flow rate) and 15 kW VRF system.

Results of all cases are discussed against results of mechanical cooling case LEVC, unless mentioned otherwise. Mechanical cooling does not add moisture and hence does not increase humidity ratio (HR) but certainly increases RH while cooling. DEC adds moisture in the space and increases RH and HR both while cooling. RH being an important parameter in the perception of thermal comfort, it is important to study and compare zone indoor environment in terms of DBT and RH both. Unmet hours in this study are based on zone DBT only and not based on operative temperature or RH criteria.

Analysis of Base Case: LEV

This case has only lighting load, equipment load and cooling load addition due to minimum ventilation air flow rate of 0.11m^3/s. Here ventilation fans are the only HVAC energy component. Annual energy for lighting, equipment and ventilation are 2764, 5799 and 232 kWh respectively for a 194 m^2 office. Thus HVAC EPI is 1.2 kWh/m^2-yr and total EPI is 45.3 kWh/m^2-yr. But simulation predicts 2791 unmet hours out of 3130 office working hours [(365-52 Sunday)*10 hours per day]. This means only 339 office working hours are comfortable.

Resulting indoor environmental condition in this case are:

- Unmet hours: 2791 (10.8% comfortable)
- RH range: 11%-76%. average 43.5%,
- DBT range: 23.5°C-44.6°C, Average 34.0°C

It should be noted that the highest DBT is 17.6°C (44.0°C -27.0°C) above the acceptable limit of 27°C.

Analysis of Reference Case LEVC: Mechanical Only Cooling

LEVC is an optimized case with VRF system size of 15.0 kW and total VRF indoor unit (IDU) air flow rate of 0.91 m^3/s providing minimum ventilation air flow rate of 0.11m^3/s. Simulation predicts 293 combined unmet hours. Unmet hours for open office, reception, and cabins zone are 254, 258 & 273 respectively. Difference between combined unmet hours (293 hour) and unmet hours for the highest unmet hour zone (273 hour) indicates that unmet conditions indifferent zones occur at different timings. LEVC is then referred to as reference case for comparison with DEC or integrated cooling system cases. End-use consumption details for this case are tabulated in Table 1.

Table 1: End-use consumption for Reference Case (LEVC)

End-use	Annual consumption (kWh)	Sub-total (kWh)	End-use EPI (kWh/ m^2-yr)	Total EPI (kWh/ m^2-yr)
Lighting	2764	2764	14.3	99.9
Equipment	5799	5799	29.9	
HVAC AHU fans + VRFODU (15 kW) + VRF IDU	236 + 7961 +2600	10797	55.7	
Total consumption		19360	-	

Resulting indoor environment condition in case LEVC or LEVC (0.11 m^3/s 15.0 kW) are as follows:

- RH range: 16%-84%. average 50.0%, highest on 25th July when ambient RH is 97%.
- DBT range: 22.8°C-29.4°C. Average of 26.1°C, highest on 13th May at ambient DBT is 43.9°C
- Unmet hours: 293 hours out of 3130 hours (90.6% comfortable)
- It should be noted that the highest DBT is 29.4 °C, 2.4°C above the highest acceptable limit.

Analysis of Reference Case with Higher (0.5 m³/s) Ventilation Rate: LEVC (0.5 M³/s 15.5 Kw)

LEVC (0.5 m^3/s 15.50 kW) is a special simulation optimised case with only mechanical cooling but with a higher ventilation flow rate of 0.5 m^3/s to study the effect of higher ventilation rate (as found later during analysis of evaorating cooling). Optimized VRF cooling size is 15.50 kW predicting 299 unmet hours. HVAC EPI & peak powers are 61.54 kWh/m^2-yr and 5.57 kW respectively. HVAC EPI and power are 10.5% and 7.5%higher. Higher ventilation rates in mechanical cooling cases always required higher cooling system size, consumes more electric energy and demands higher peak power in this study.

Analysis of Evaporative Cooling

Cases for evaporative cooling with 90% effectiveness are presented in this section. Pre-cooled airflow greater than minimum ventilation (0.11m^3/s) were simulated. Firstly, a 1.0 m^3/s flow was distributed according to zone floor area proportions and simulation was run. Unmet hours found in different zones were not similar. This is because different zones have distinct orientation, distinct adjacency and distinct internal heat gains and thus different cooling load requirements. Then, the flow rate in the zone with least unmet hours was reduced and the flow rate in the zone with highest unmet was increased. After several simulation iterations, optimised flow rate proportions were found out for 1.0 m^3/s total flow rate to have similar unmet hours across three zones.

Secondly, total DEC flow rates of 0.11 m^3/s, 0.25 m^3/s, 0.5 m^3/s and then up to 5.0 m^3/s in steps of 0.5 m^3/swere simulated for the optimized proportions so that individual zone unmet hours remains similar across three zones for any given flow rate. Relation between DEC flow rate and resulting unmet hour is shown in Figure 6.

Unmet hours reduce when the DEC flow rates increase up to 5 m^3/s. For a limiting flow of 30 ACH (Bhatia,

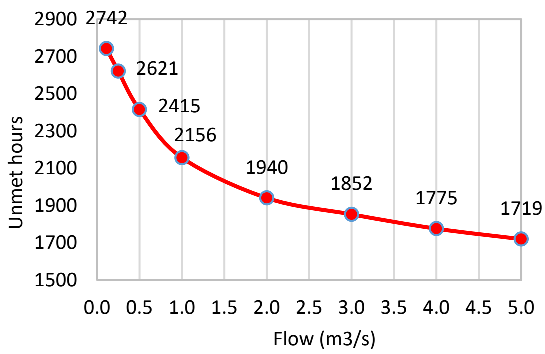

Figure 6 Unmet Hours for different DEC flow rates

2012) corresponding to 4.0 m^3/s in this study, 1775 unmet hours are observed. Relation between flow rate and unmet hours is not linear. HVAC EPI and power for limiting flow of 4.0 m^3/s is 46.3 kWh/m^2-yr and 2.7 kW respectively. For limiting flow, HVAC EPI is 17% less and HVAC power is 48% less but DEC cooling predicts 1775 unmet hours against 293 hours in LEVC case, which is not acceptable. For limiting DEC flow of 4.0 m^3/s following indoor conditions are predicted:

- RH range: 80%-97%. average 88.5%,
- DBT range: 17.2°C-33.9°C
- Unmet hours: 1775 (57%)
- Comfortable hours: 1355 (43%)

The highest temperature observed without any cooling (LEV case) was 44.1°C. Thus, DEC cooling helps reduce it to 33.9°C. However, continuous high RH condition (80-97%) remains a concern. Lower DBT value of 17.2°C in winter is also a concern.

Higher evaporative air flow rate requires larger evaporative cooling system size. Even with limiting flow of 30 ACH (4.0 m^3/s) air flow rate, unmet hours are far beyond 300 hours. This is the indication of (1) High ambient DBT hours and (2) long humid period in Ahmadabad (day long in monsoon period), adversely effecting cooling through DEC. Therefore, there is a need to explore integrated systems employing mechanical cooling with DEC that possibly predict less than 300 unmet hours, help reduce cooling energy and provide better indoor conditions at the same time.

Analysis of Integrated System- Mechanical and Evaporative Cooling

In this case, DEC and mechanical cooling (15.0 kW) both are added to the Base case model. To start with, VRF cooling system with total IDU airflow of 0.91 m^3/s as obtained from optimised LEVC case simulation) is fixed for all further simulations.Unmet hours and HVAC EPI for different DEC flow rates are plotted as shown in Figure 7

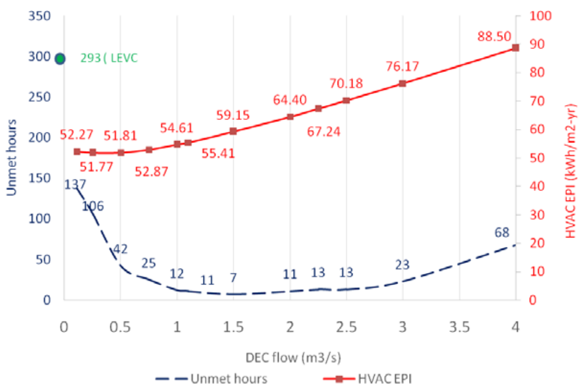

Figure 7 Effect of DEC air flow on unmet hour and HVAC EPI

Effect of these flow rates on HVAC EPI & power and resulting indoor environment are discussed. Further, Effect of switching off or delay in DEC start time in following three situations were also explored

- Effect of DEC switching off in three highly humid months to gather,
- Effects of switching off DEC - month by month
- Effect of delayed DEC start in the winter morning time

Ideal DEC Flow Rates in the Context of HVAC EPI and Unmet Hours

From Figure 7, it is observed for the integrated case with 15.0 kW VRF system and DEC air flow rate of 0.11 m^3/s, predicts 137 unmet hours. Increasing flow rate up to 1.5 m^3/s helps to reduce unmet hours down to 7 hours. Further increase in flow rate results in increased unmet hours. So, 1.5 m^3/s is the ideal DEC air flow rate for minimum unmet hours. For an airflow rate of 0.11 m^3/s HVAC EPI is 52.8 kWh/m^2-yr and unmet hours are 137. Increasing flow rate to 0.25 m^3/s, HVAC EPI reduces to 51.77 and unmet hours are reduced to 106 hours. A subsequent increase in flow rate to 0.5 m^3/s, HVAC EPI is increased negligebly (by .04 kWh/m^2-yr) to 51.81 kWh/m^2-yr but unmet hours are reduced to 42 hours. Further increase in flow rate up to 4.0 m^3/s continuously increases HVAC EPI. For 4.0 m^3/s flow rate, HVAC EPI is 88.5 kWh/m^2-yr with 68 unmet hours. The flow rate of 0.25 m^3/s and 0.5 m^3/s have similar HVAC EPI but have 106 and 42 unmet hours respectively. Thus 0.5 m^3/s is an ideal DEC flow for minimum unmet hours that provides double the fresh air at the similar HVAC EPI. Peak HVAC power, in this case, is 5.46 kW. HVAC EPI is 7.0% lower but HVAC power requirement is 5.4% higher.

Energy and Environment Condition for Optimized DEC Flow

When 15.0 kW VRF cooling complemented by DEC cooling with 0.5 m^3/s flow rate, simulation predicts just 42 unmet hours, it can be optimized in terms of VRF system size for 290-300 unmet hours range. LEVC + DEC (0.5 m^3/s 10.75 kW) is such an optimized case with VRF cooling size of 10.75 kW predicting 297 unmet hours. HVAC EPI and power are 46.3 kWh/m^2-yr and 4.10 kW respectively. HVAC EPI and power are reduced by 17.0% & 21.0%. VRF cooling system size is reduced by 28.6%. An important benefit is that this case provides 3.5 times more treated fresh air. Indoor environment conditions in this case are:

- RH: 40% - 89%.; Average 64.5% on 25th July, when ambient RH is 96%
- DBT: 19.9°C - 29.0°C; Average 24.5°C on 8th June when ambient DBT is 37.8°C
- Unmet hours: 297 hours; within the limit

In this case, unmet hours are within 290-300 hours range. Highest DBT is 29.0°C, which is just 2.0°C above the acceptable limit. Maximum RH is increased

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by 5%. There is no continuous high relative humidity condition. Highest DBT is 0.4 °C less than that in LEVC case and it is more desired even in the similar unmet hour conditions. Highest indoor DBT condition is delayed by 26 days (From 13th May to 8th of June). This means a Hybrid option helps reduce and level peak electricity demand helping utility company. Integrated case requires 4.25 kW smaller VRF system size. At 3.71 COP, 4.25 kW systems can provide 15.77 kWh cooling in an hour. For this situation, DEC will require maximum 25 litres of water an hour when there is a full evaporative potential. (based on 2260 kJ/kg latent heat of evaporation of water, as discussed earlier in the introduction section.

Energy and Environment Condition for 1.5 m^3/s DEC Flow Rate

As seen in Figure 7, least seven unmet hours are observed in the integrated system with the DEC flow of 1.5 m^3/s.More simulations were run with reduced VRF size. have unmet hours within 300. LEVC + DEC 1.5m^3/s 9.6 kW is a case with just 9.6 kW VRF cooling system size. Though HVAC EPI (53.0 kWh/m^2-yr) is 5% less, peak HVAC power (5.63 kW) is 9% more. However, the cooling system size is 36% smaller compared to LEVC case. One important benefit is that it provides 12.5 times more fresh air (11.4 ACH) at 5% less HVAC EPI. This is a good integrated option when the performance of mechanical cooling system is degraded.

Indoor environment conditions in this case are:

- RH: 61%-93%. Average of 77%, highest on 25th July when ambient RH is 96%
- DBT: 17.8°C- 28.9°C; Average 23.4°C, highest on 8th June when ambient DBT is 37.8°C
- Unmet hours: 293 hours

Effect of DEC Switching Off for Humid Months (for DEC Air Flow Rate of 0.5 m^3/s)

Continuous high humidity in monsoon and low DBT in winter months are matters of concern. July through September are humid months in Ahmadabad. To study the effect if DEC is switched off during these months, more simulations were carried out with a minimum ventilation requirement for these three months through AHU and with 0.5 m^3/s DEC flow for other nine months.

Optimized case, (LEVC (0.5 m^3/s 12.5 kW) (No DEC July + Aug + Sept)) is with 12.5 kW cooling system size. HVAC EPI 50.0 kWh/m^2-yr is 10.2% less, peak HVAC power (4.68 kW) is 9.7% less with 17% smaller VRF size. Indoor environment conditions for this case are:

- RH: 40%-84%. Average of 62%, highest on 25th July when ambient RH is 97%
- DBT: 20.0°C-28.7°C. Average (Arithmetic mean) of 24.4°C, Highest on 8th June when Ambient DBT is 37.8°C
- Unmet hours: 296 hours

In this case, the highest DBT is 28.7°C, which is just 1.70°C compared to 2.4°C (as calculated for LEVC case) above the acceptable limit. This means, that Indoor highest temperature is reduced by 0.7°C and it is more desired even in the similar unmet hour condition. Maximum RH is 84%. There is no continuous high RH condition compared to DEC cooling throughout the year. Highest DBT is observed on 8th June. This helps delay and level peak power requirement by 26 Days.

Effect of Switching Off DEC for a Whole Month One by One

More twelve simulations were carried out to see the effect on HVAC EPI andHVAC power if DEC is switched off for a whole month for optimized integrated case LEVC + DEC for VRF size 10.8 kW and DEC flow rate of 0.5 m^3/s.

It is observed that November through February are the four months when DEC can be switched off without adding any unmet hours. But HVAC EPI & power increases negligibly. If DEC is switched off between March to September, unmet hours rise above 300 in each case. The month of May is worst affected when unmet hours increase to 439 hours. DEC can be switched off in October without adding unmet hour but HVAC EPI increases but not HVAC power. It should be noted that from March to September, unmet hours become unacceptable. So, switching off DEC in these seven months is not a good option as far as integrated cooling is and HVAC EPI and power are concerned.

Effect of the Delayed Start of DEC for a Whole Month

December, January, and February have colder mornings in the hot and dry climate of Ahmadabad. DEC if switched on at regular schedule time of 08:30 h, unnecessarily cools the space when it is not required. More simulations were carried out by delaying DEC start time from the usual time of 08:30.

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DEC start can be delayed till 09:00, 10:00 and 09:30 for these months respectively without increasing HVAC EPI. These winter months and timings are ideal from point of view of inspection and maintenance of cooling systems with least or no discomfort.

CONCLUSION

Generally, small offices in hot and dry zones, employ mechanical cooling which results in high HVAC EPI and high peak HVAC power. Direct Evaporative cooling even with limiting flow of 30 ACH, cannot provide year-round comfort. Hence this study focuses on an integrated system which helps reduce mechanical cooling system size, HVAC EPI &HVAC peak power at an acceptable limit of 300 unmet hours.

For an integrated system filtered fresh air pre-cooled by DEC enters the conditioned space through AHU evenly distributed in the office space and the return air from the conditioned space goes out as shown in Figure 5 in methodology section.

VRF ID unit cools the zone air when set point temperature is not met by pre-cooled direct air. VRF cooling can be done through cooling coils placed in the AHU or directly in the individual zone. Return air can be exhausted through AHU or directly from the space. Indoor environment results of various simulation cases with and without cooling system and integrated system are summarized in Table 2.

VRF system size, HVAC EPI & power and resultant unmet hours are summarised in Table 3.

For optimized mechanical cooling case, LEVC with a 15.0 kW VRF system predicts 293 unmet hours. HVAC EPI &peak powersare 55.7 kWh/m^2-yr and 5.18 kW respectively.

An ideal integrated option is LEVC + DEC (0.5m^3/s 10.8 kW) predicts 297 unmet hours with 10.8 kW VRF system at 46.2 kW/m^2-yr HVAC EPI and 4.09 kW peak power.

Table 2 Summary of indoor environment for important cases

Optimized Case	Indoor environment					
	DBT			RH		
	Min	Max	Av	Min	Max	Av
	°C	°C	°C	%	%	%
LEV(.11 m^3/s)	23.5	44.6	34.3	11.1	76.2	43.2
LEVC (0.11 m^3/s)	22.8	29.4	26.1	15.8	84.4	50.1
LEV + DEC (0.5 m^3/s)	17.2	33.9	25.6	80	97	89
LEVC + DEC (0.5 m^3/s)	19.9	29.0	24.5	39.8	89.0	64.4
LEVC + DEC (Except July, Aug. & Sept.)	20.0	28.7	24.4	40.0	83.8	61.9

Table 3 Summary of various system for unmet hours cooling system size and Energy

Optimized Case	Unmet hours (Out of 3130)	VRF system size	HVAC EPI	Peak HVAC Power
	Hours	kW	kWh / (m^2-yr)	kW
LEV (.11 m^3/s)	2791	-	1.2	-
LEVC (0.11 m^3/s)	293	15.05	55.7	5.18
LEV + DEC (0.5 m^3/s)	1775	-	46.3	2.7
LEVC + DEC (0.5 m^3/s)	297	10.80	46.2	4.09
LEVC + DEC (Except July, Aug. & Sept.)	296	12.5	50.0	4.68
LEVC (0.5 m^3/s)	299	15.50	61.54	5.57

Thus, the integrated system helps reduces VRF cooling size by 28%, help reduce annual cooling energy need by 17% and help reduce peak HVAC power by 21%. as shown inTable 3.

Hybrid system help increase minimum RH level from 16% to 40% but adversely effecting in humid months by increasing RH from 84% to 89%, which cannot be overlooked against many benefits it offers. Effect of switching off DEC for any given month during a year results in increased HVAC EPI. So, it is not advisable. DEC can be switched on little later in colder months of December January and February by 30, 90 and 60 minutes respectively from the usual time of 08:30 hour without increasing HVAC EPI for the case studied. For providing similar amount of fresh air as in the integrated option LEVC + DEC, mechanical only cooling will require 43.5% bigger cooling system. It will also result in 33.2% higher HVAC EPI and 36.2% higher peak HVAC power compared to integrated option.

Moreover, lower HVAC peak load in the integrated option requires smaller infrastructure (wires, safety devices, main cable, at user's place.

HVAC energy savings resulting from the integrated system in Hot and dry climate (Ahmadabad with highest DBT 44.0°C) is 17% whereas in literature studies savings are stated to be as high as 50-60%. However, it should be noted that 50-60% savings are true for the places where highest DBT is in the range of 28°C-30°C only. The difference between ambient temperature of 28°C-30°C to 44.0°C incase of Ahmedabad is about 15.0°C is very crucial. Thus, highest DBT of the location is one very important reason for this difference in energy savings.

Evaporative cooling systems provide better indoor air quality resulting from 350% more fresh air than the minimum ventilation requirement. Reduced mechanical cooling system size help reduce lower life cycle cost, help reduce carbon footprint in its manufacturing, transporting and installation. Reduced energy consumption helps to reduce electricity generation – leading to lesser pollution and lesser water consumption at power generation facility.

However, it should be noted that integrated system becomes little complex to operate, when DEC, is integrated with AHU. DEC systems require additional space. Continuous good quality water feed (< 400 ppm dissolved solids) is required along with periodic draining of sump water to avoid salt build-up and mosquito breeding. Higher continuous relative humidity is conducive to growth of mould and mildew leading to unhygienic and unhealthy indoor conditions. Humid conditions may harm building internal walls, floor, ceilings and furniture. This problem can be resolved by advanced paints and coatings to some extent.

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QUANTITATIVE AND QUALITATIVE COMPARISON OF THE ENERGY SECTION IN THE PREVALENT GREEN BUILDING RATING SYSTEMS IN INDIA

Author Chitrangada Bisht[1], Akshay Pahade[2], Prachi Jaiswal[2], Kiran Giri[2]

[1]*Independent Consultant*
Mumbai, India
chitrangada.bisht@gmail.com

[2]*Grattitude Synergy LLP*
Pune, India
akshay.pahade@grattitude.in

ABSTRACT

Building industry has been at the forefront of energy efficiency since the past few decades with a large number of building owners embracing voluntary green building rating systems such as LEED, GRIHA and IGBC. These rating systems assess the buildings on various parameters of sustainability while giving highest weightage to energy efficiency. To enable faster adoption of green construction practices, many civic bodies have also offered incentives for developers such as additional Floor Area Ratio (FAR) for compliance with third party certifications.

The overall approach for appraising the energy efficiency of buildings remains similar in all the rating systems, which is to calculate the power consumption per unit area and demonstrate reduction from an established baseline (w.r.t. ASHRAE 90.1 / ECBC) but these baselines vary with each rating system.

The civic bodies and building owners need to often weigh these options but the technical comparison to do so is not readily available. This paper compares the energy consumption of a building by complying with minimum level of performance in each rating system, namely LEED, GRIHA and IGBC, by comparing the two most prevalent energy standards – ASHRAE 90.1 and ECBC. The energy consumption is calculated in kWh per unit area by simulating a fully air-conditioned typical commercial office building in New Delhi, India using EQuest. In addition to the quantitative comparison, the paper also provides a qualitative comparison of the energy efficiency requirements set forth in these ratings and standards.

Keywords—ASHRAE ECBC Comparison, Energy Efficiency in Buildings, Green Buildings, Building Energy Codes

INTRODUCTION

Building sector accounts for one third of the total energy consumption in India, out of which commercial buildings account for about 9%.[1] Electricity consumption in Commercial Buildings is estimated to increase more than 3 times by 2021, from 2010-11 level. The average household is likely to consume 5 times more electricity in 2020 than in 2000. As compared to 2011, by 2021 the electricity consumption by space heating/cooling appliances will grow by 180%.

Initiatives are being taken up globally to promote energy efficiency in the building sector. A comprehensive set of policies have been adopted by India to move the country towards more energy efficient buildings. A major step towards exploiting energy efficiency potential in India was the enactment of the Indian Energy Conservation Act in 2001, under which a dedicated Bureau of Energy Efficiency (BEE) was created. The BEE has since launched a number of policies targeting the buildings sector, including the development and introduction of Minimum Energy Performance Standard (MEPS) and labelling for equipment and appliances; the launch of the Energy Efficiency Building Codes (ECBC); the promotion of the energy efficiency in household lighting through a Clean Development Mechanism (CDM) project to introduce compact fluorescent lamps (CFLs); and a dedicated project to enhance technical capacities and access to finance for small and medium enterprises.[2]

Energy performance of buildings is also being enhanced through the voluntary building certification

[1] CEA, 2017

[2] IEA

systems in the market in addition to the regulatory framework established by the BEE.

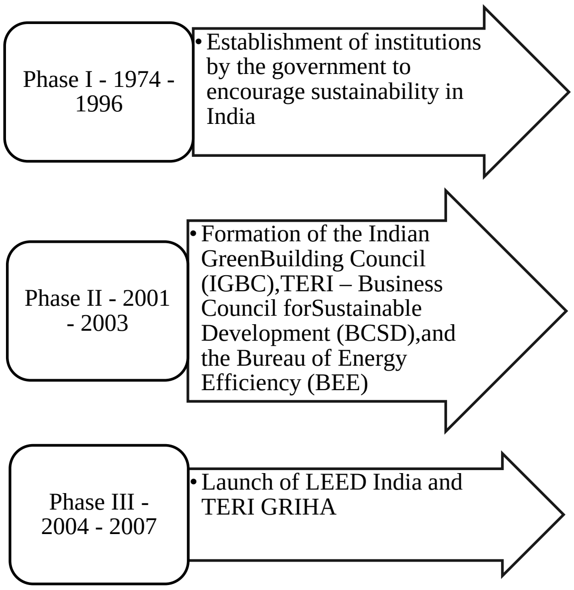

Figure 1: Green Building timeline in India (Potbhare, 2008)

The green building movement in India really accelerated after the formation of Indian Green Building Council (IGBC) in 2001. The LEED Rating was launched in India in 2004 by IGBC. In 2008 GRIHA rating was launched in India by The Energy and Resources Institute (TERI). Now LEED is implemented in India by the US Green Building Council (USGBC) while IGBC has its own set of rating systems under the IGBC labels. Today, IGBC, LEED and GRIHA are the three most prevalent building rating systems in India.

All these three rating systems employ similar methodology for project evaluation, i.e. point based assessment. The points cover various strategies panning different themes like site planning, water efficiency, waste management, energy efficiency, and operations and maintemance for appraising projects. The projects are awarded a merit rating based on the benchmark of points put forth by the system.

While ECBC sets forth a mandatory minimum level of performance, the green rating systems reward building performance over and above the minimum performance. Acknowledging the role played by these volutary rating systems, government has rolled out various incentives with the intent of mainstreaming green buildings and energy efficiency. Buildings are a state and municipal subject in India and hence these incentives are mostly localized. The incentives include financial in the form of development fee and property tax rebates and provision for additional FAR/FSI depending on the level of performance. This aproach of incentivising projects complying with voluntary performance is being widely accepted and more new states, cities and municipalities are considering rolling out similar schemes.

This paper aims to compare the parameters specifically on energy efficiency in each of the rating system, understand the key differences and compare the energy performance values achieved by complying with each.

METHODOLOGY

A typical small office building located in NCR is being used as a case study. This building is modeled in EQuest to quantify and compare the energy consumption.

LEED, IGBC and GRIHA have several variants based on building typologies and project size. The most relevant variant to be adopted for the above case study were identified as LEED BD+C (Building Design & Construction) Version 4, IGBC Green New Buildings Rating Version 3 and GRIHA Version 2015 respectively.

During assessment of the energy sections it was understood that each of the aforementioned rating system relies on a building energy code for compliance and achievement of points.

Table 1: Rating systems and respective energy codes

Rating System	**Reference Energy Code**
LEED BD+C V4	ASHRAE 90.1-2010 or USGBC-approved equivalent standard for projects outside the U.S.[a]
IGBC Green New Buildings V3	ASHRAE 90.1-2010 or ECBC 2007
GRIHA New Buildings V2015	ECBC 2007
GRIHA New Buildings V2019[b]	ECBC 2017

a) USGBC accepts only ASHRAE 90.1-2010 in India and hasn't yet released any directive on compliance with ECBC yet.

b) GRIHA has recently lunched Version 2019, however it is yet to be implemented at the time of writing this paper.

Whereas IGBC accepts compliance with any of the two codes ASHRAE 90.1-2010 or ECBC 2007. IGBC hasn't yet adopted ECBC 2017. GRIHA being an indigenous rating system designed for India accepts compliance only with ECBC.

It is noteworthy that both ASHRAE and ECBC have come forth with new codes, but only GRIHA has upgraded its requirement with the latest ECBC. LEED and IGBC are yet to adopt the latest codes.

In this paper however, it was decided to model the buildings as per the updated codes, namely ECBC 2017 and ASHRAE 90.1-2010.

ECBC 2017 has been in circulation for quite some time and has been incorporated in GRIHA V2019 but not in IGBC. IGBC has not been updated since 2015 and it is anticipated that IGBC may also adopt ECBC 2017 very soon. LEED V4 which is most recently updated is still referring to ASHRAE 90.1-2010. Hence, the energy efficiency was compared between ECBC 2017 and ASHRAE 90.1-2010.

The energy performance for the older codes will be intrapolated based on the 2018 publication by CEPT University named **Impact of ECBC on building energy consumption at city level, Phase 3**.

Due to limitation of time and resources, only the baseline case or minimum performance standards are being assessed for each rating. There is further scope for modeling and comparing higher levels of certification and the ASHRAE 90.1-2013 as well.

BUILDING INFORMATION AND MODELING ASSUMPTIONS

A 7 (G+6) storeyed office building located in the National Capital Region (NCR) has been considered for this comparative analysis. The Ground Floor has parking and the remaining 6 floors have a typical open office layout. Footprint of this building is around 7,500 sq.ft. and the total built-up area is 52,500 sq.ft. Out of this, 36,540 sq.ft. (70%) is air-conditioned. Since, the building is located in the NCR, hence the weather file of New Delhi is used for the analysis.

The Window to Wall Ratio (WWR) in both cases is considered as 40%, as required by both ECBC 2017 and ASHRAE 90.1. Building envelope input parameters as below[3]:

Table 2: Building envelope input parameters

Construction	ASHRAE 90.1 - 2010	ECBC 2017
Ext. Wall – above grade, U-value	0.124	0.111
Roof, U-value	0.063	0.05815
Wall - below grade, U-value	1.14	N/A
Floor, U-value	0.35	N/A
Doors, U-value	0.7	N/A
Glass, U-value	1.2	0.53
Glass, S.C.	0.287	0.31
Glass, VLT	N/A	0.27

Table 3: Lighting power density (LPD, W/sq.ft.)

Space type	Area (sq.ft.)	LPD, ASHRAE	LPD, ECBC
Closed Office	13210.3	1.11	0.93
Parking Garage	4286.7	0.19	0.20
Open Office	4315.8	0.98	0.93
Lift Lobby	1536.9	0.64	0.85
Stairways	3948.6	0.69	0.51
Void	1326.1	0	0.00
Restroom	4184	0.98	0.72
Elect/Mech	241.3	0.95	0.66
Recreation	586.9	0.73	0.72
Food Prep	900.2	0.99	1.12
Conference	555.3	1.23	1.07
Dormitory	286.8	0.38	0.66
Fitness	299.5	0.72	1.27
Fitting Room	139.1	0.87	0.85
Dining	442.6	1.31	1.31
Multipurpose	172.8	1.23	1.07
Reading Area	546.5	0.93	0.93
Stacks	908.4	1.71	0.48
Storage	252.6	0.63	0.63
Corridor	14445.5	0.66	0.66
Total	52585.9	0.81	0.72

Equipment power density: 0.75 W/sq.ft. in both models

Infiltration loads: 0.75 air-changes/hr in both models

ASHRAE 90.1-2010 Baseline HVAC Inputs:

- The office building has total 7 floors, and the fuel used is mainly electricity from the grid. Hence the applicable system type would be System 8: VAV with PFP boxes. The VAVs are served by central chilled water plant.
- As the cooling load for building is less than 300 TR, 1 water cooled screw chiller has been

[3] U values are in Btu/h.sq.ft.F

considered in the model, with a COP of 4.51 (Table 6.8.1C).

- Baseline equipment has been oversized by 25% for heating and by 15% for cooling.
- Fan systems have been made to operate continuously when occupied and cycled to meet loads when unoccupied.
- CHW supply temperature has been set at 44 deg F, whereas return is considered as 56 deg F (delta of 12 deg F)
- Chilled water pumps have been modelled with pump power of 22 W/gpm
- On the condenser side, one axial fan cooling tower has been modelled with 2 speed fans and an approach of 10 deg F. Condenser water pumps have been modelled with pump power of 19 W/gpm.
- For VAV systems, fans have been sized at 50% of peak design flow rate. The parallel fan powered units have been modelled with 0.35 W/cfm fan power and minimum volume set-points of 30% of peak design flow rate.

ECBC 2017 Baseline HVAC Parameters:

- According to ECBC, the baseline HVAC system type is selected as VRF system.
- The VRF system is a non-standard system type in eQuest software, and hence alternative modelling methodologies have to be used to model work-arounds. One such methodology published by Daikin has been referred while modelling the VRF system in this case.
- The part-load performance curves were imported in the eQuest model and were linked with all air-side systems to reflect their part load efficiencies in energy performance. According to the methodology, systems have been modelled as Packaged Single Zone with Heat Pumps and configured as per the indoor units. The efficiencies have been modelled as per respective outdoor units. Fan energy has been included as kW/cfm.

Schedules and Thermal Comfort Criteria

Both the ASHRAE 90.1-2010 as well as ECBC 2017 models consider similar setpoints and schedules. The schedules for occupancy, lighting, equipment, HVAC are considered as per ECBC 2017 for both the models. Fan schedule is set to operate one hour before & after the regular occupancy hours of 9 am to 6 pm. Profiles for regular weekday, Saturday and Sunday/holiday are considered in the weekly schedules. Scheduled setpoints are considered as 75 deg F for cooling and 70 deg F for heating during occupied hours.

RESULTS AND DISCUSSION

QUALITATIVE COMPARISON

In the qualitative comparison this paper tries to understand and list the key differences in compliance requirements, which are otherwise not captured in the simulated energy consumption results.

1. **Overall weightage to energy efficiency and point distribution**

LEED, IGBC and GRIHA have assigned 16%, 15% and 13% weightage to energy efficiency and 30%, 28% and 20% respectively to the overall energy section. LEED has given the highest while GRIHA has given the least weightage to energy efficiency among the 3 ratings.

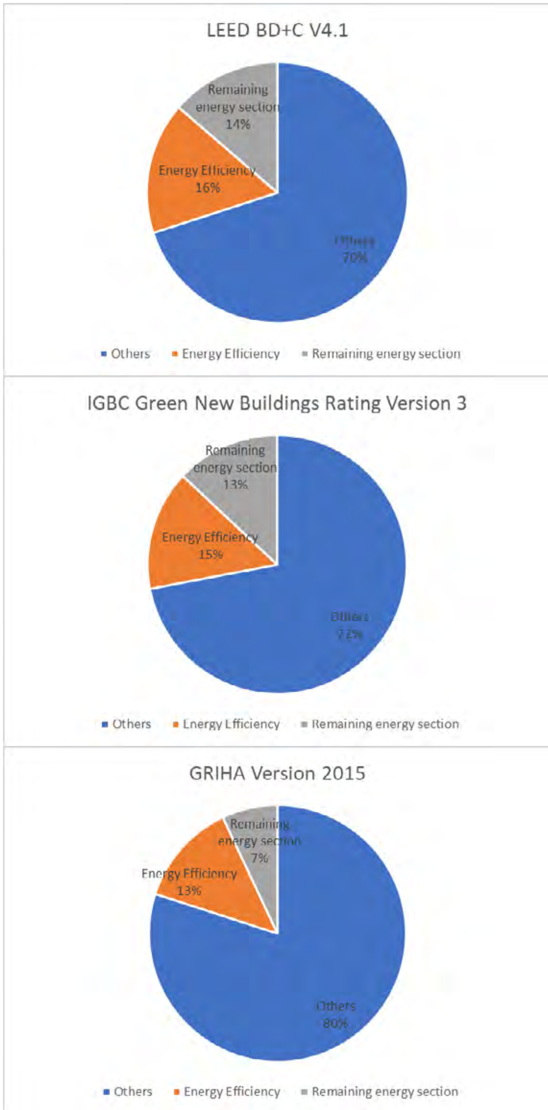

Figure 2 Percentage weightage of energy efficiency in the 3 rating systems.

The point distribution in the energy section in each of the rating system has been tabulated below. In this

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paper the quantitative comparison has been carried out for the requirement highlighted in yellow.

Table 4: LEED BD+C V4 - Point distribution in the energy section

Name of Section - Energy & Atmosphere		
	Credit	**Points**
Prerequisite	*Fundamental Commissioning and Verification*	*Required*
Prerequisite	*Minimum Energy Performance*	*Required*
Prerequisite	*Building-Level Energy Metering*	*Required*
Prerequisite	*Fundamental Refrigerant Management*	*Required*
Credit	Enhanced Commissioning	6
Credit	Optimize Energy Performance	18
Credit	Advanced Energy Metering	1
Credit	Demand Response	2
Credit	Renewable Energy Production	3
Credit	Enhanced Refrigerant Management	1
Credit	Green Power and Carbon Offsets	2
	Section total	**33**

Table 5: IGBC Green New Buildings V3 - Point distribution in the energy section

Name of Section - Energy Efficiency		
S.No.	**Credit**	**Points**
EE Mand. Req 1	*Ozone Depleting Substances*	*Required*
EE Mand. Req 2	*Minimum Energy Efficiency*	*Required*
EE Mand. Req 3	*Commissioning Plan for Building Equipment & Systems*	*Required*
EE Credit 1	Eco-friendly Refrigerants	1
EE Credit 2	Enhanced Energy Efficiency	15
EE Credit 3	On-site Renewable Energy	6
EE Credit 4	Off-site Renewable Energy	2
EE Credit 5	Commissioning, Post-installation of Equipment & Systems	2
EE Credit 6	Energy Metering and Management	2
	Section total	28

In LEED and IGBC all the 18 and 15 points in the highlighted credits namely Optimize Energy Performance and Enhanced Energy Efficiency are awarded based on the percentage reduction from the ASHRAE base case. The requisite compliance is as shown in the table below.

Table 5: GRIHA V3 - Point distribution in the energy section

Name of Section - Energy Efficiency		
S.No.	**Criteria**	**Points**
Criterion 8	Energy efficiency	13
Criterion 9	Renewable energy utilization	7
Criterion 10	Low ODP materials	0
	Section total	20

It is noteworthy that despite the percentage variations, all the rating systems have awarded highest weightage to the energy section and hence it can be stated that **energy efficiency is the most important parameter in all green building rating systems.**

2. Climate zones

ASHRAE 90.1-2010 assigns a single climate zone to entire India whereas ECBC 2017 has provided 5 climate zones for India. However, while adopting a whole building simulation, climate data is used in the model which remains same for both models and does not affect the ultimate energy efficiency number.

ECBC 2017 has provided different minimum Energy Performance Index (EPI) benchmarks for each climate zone for different typologies of buildings. Although, in this case study baseline was modelled utilizing the mandatory requirements of prescriptive approach and hence it was automatically below the prescribed benchmark.

On the other hand, for LEED, ASHRAE 90.1 doesn't have an EPI number but it has a defined base case that will determine the unique benchmark for each project based on design.

3. Parameter for compliance

IGBC, LEED and GRIHA, all award points based on energy savings whereas LEED awards points based on utility bill savings or cost savings. Variable energy costing of a sliding scale may encourage projects to achieve higher energy efficiency.

4. Compliance method

For meeting the mandatory energy savings, LEED V4 and IGBC V3 allow the choice between a prescriptive compliance method or whole building simulation methodology depending on the building specifications but GRIHA has mandated all the mandatory sections in the prescriptive compliance mode of ECBC.

To achieve points above mandatory requirement, building energy simulation is a must in all ratings.

For the project being studied in this paper, the compliance methodology is of comparable difficulty for all three rating systems.

Compliance requirement in LEED BD+C V4

- Three options are available for mandatory compliance depending on project specifications:
  - o Whole building energy simulation to demonstrate compliance with ANSI/ASHRAE/IESNA Standard 90.1–2010, with errata
  - o Prescriptive Compliance: ASHRAE 50% Advanced Energy Design Guide
  - o Prescriptive Compliance: Advanced Buildings™ Core Performance™ Guide
- Fundamental commissioning is mandatory
- Minimum 5% reduction for commercial new construction buildings from Base Case
- Optimize energy performance 1to18 points

Compliance requirement in IGBC New Construction V3

- To fulfil the mandatory requirement of minimum energy efficiency of IGBC, projects must comply with ECBC 2007 or ASHRAE 90.1-2010 through either whole building simulation method or prescriptive approach.
- Commissioning of systems is mandatory
- 1 to 15 Points are awarded based on demonstrated saving from ASHRAE 90.1 Base Case.

Table 6: Percentage reduction in Energy cost over ASHRAE Standard 90.1-2010 for points in LEED and IGBC.

Percentage of Energy Cost Savings over ASHRAE Standard 90.1-2010 Base case	LEED BD+C V4	IGBC Green New Buildings
6%	1	1
8%	2	2
10%	3	3
12%	4	4
14%	5	5
16%	6	6
18%	7	7
20%	8	8
22%	9	9
24%	10	10
26%	11	11
28%		12
29%	12	
30%		13
32%	13	14
34%		15
35%	14	
38%	15	
42%	16	
46%	17	
50%	18	

Compliance requirement in GRIHA V 2015

- Project must meet all mandatory points of ECBC. Although Following are exemptions for commercial buildigs:
  - o 5.2.1 – Natural ventilation
  - o 7.2.1.1 – Automatic lighting control for spaces bigger than 500 m^2 and
- All fans must be BEE star rated
- 2 Points are awarded for peak heat gain
- 1 point is awarded for minimum luminous efficacy of 75 lumens/watt for all exterior lights
- Reduction from GRIHA EPI is mandatory, i.e. 90 kWh/m^2/year
- 10 more points are awarded on subsequent reduction from EPI Benchmark

Table 7: GRIHA Thresholds for Building Envelope Peak Heat Gain Factor (W/sqm)

Climate	Threshold
Composite/Hot & Dry	40
Warm and Humid	35
Moderate	30

Table 8: Percentage reduction in energy consumption over GRIHA EPI for points in LEED and IGBC.

Reduction from EPI benchmark	GRIHA V 2015	GRIHA V 2019
0 - 10%	2	_
10% - 20%	3	1
20% - 30%	5	2
30% - 40%	7	4
40% - 50%	10	6
>50%		8

FINDINGS OF THE QUALITATIVE COMPARISON

It was found that all the rating systems are similar in approach. They are point based and energy efficiency points are awarded based on percentage reduction from a pre-defined energy benchmark.

Primarily, interior lighting and air-conditioning loads are taken into account for electrical consumption.

Extensive energy simulation in a software is required for demonstrating compliance in all the three rating systems because all the rating systems require the annual energy consumption. The real annual energy consumption number cannot be known unless the building is fully occupied which may take a few years. In the absence of the real data, the next best option is calculations with the help of a simulation tool that can take into account all the factors like weather, material specifications, energy efficiency measures etc.

The table in the next page summarises the qualitative parameters in the three rating systems.

Table 9: Summary of the qualitative comparison of energy efficiency criteria in the three rating systems

	LEED BD+C V4	IGBC Green New Buildings	GRIHA V 2015
Assessment Style	Point based	Point based	Point based
Total achievable Points	110	100	100
Points for complete Energy Section	33	28	20
Points for energy efficiency	18	15	13
Criteria for achieving points for energy efficiency	Percentage reduction in annual energy cost factoring-in the actual utility cost calculated based on energy consumption reduction from a defined energy consumption benchmark	Percentage reduction in annual energy cost factoring-in the actual utility cost calculated based on energy consumption reduction from a defined energy consumption benchmark	Percentage reduction in annual energy consumption from the defined energy consumption Benchmark
Energy consumption Benchmark	Calculated as per ASHRAE 90.1 appendix G specifications. This number is unique to every project depending on the building design.	Calculated as per ASHRAE 90.1 appendix G specifications. This number is unique to every project depending on the building design.	Adopted from ECBC EPI (Energy Performance Index) benchmark. The number is fixed for each typology in a given climate zone.
Reference Standard	ASHRAE 90.1	ASHRAE 90.1 or ECBC*	ECBC
Calculation methodology	Energy simulation. Alternatively, prescriptive approach for compliance is available for some cases	Energy simulation. Alternatively, prescriptive approach for compliance is available for some cases	Energy simulation. Prescriptive approach is not available under this GRIHA variant.

**Although projects can comply with IGBC Green New Buildings mandatory compliance through either ASHRAE 90.1 or ECBC, for achieving the 15 points projects need to demonstrate reduction from ASHRAE 90.1 base case.*

QUANTITATIVE COMPARISON

Table 10: Comparison of the energy simulation results carried out in eQUEST for the two models

Electric Consumption (kWh)	ECBC 2017	ASHRAE 90.1 - 2010	Difference
Space Cool	2,07,803	1,66,541	19.9%
Heat Reject.	-	28,148	
Space Heat	4,365	82,721	-1795%
Vent. Fans	1,92,464	77,004	60.0%
Pumps & Aux.	-	98,848	
Misc. Equip.	95,176	95,176	0.0%
Area Lights	1,10,076	1,25,153	-13.7%
Total	**6,09,884**	**6,73,589**	**-10.4%**
Total EPI (kWh/sq.ft/yr)	**11.60**	**12.81**	**-10.4%**

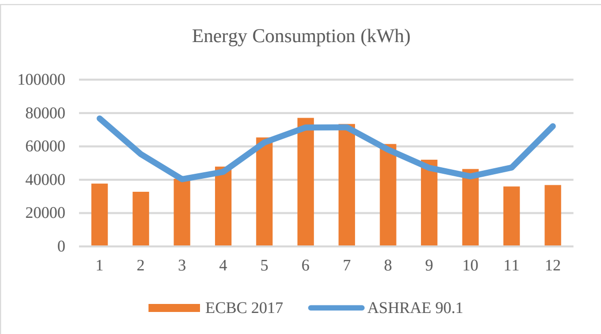

Figure 3 Comparative annual energy consumption graph

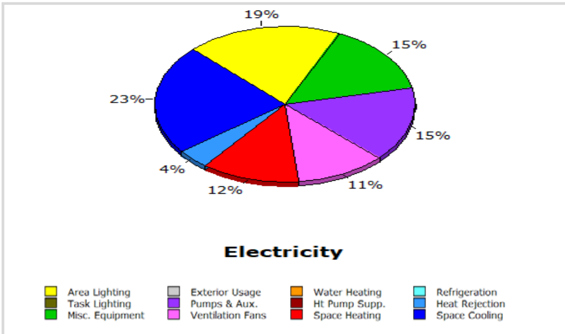

Figure 4: Annual Energy Consumption by End-Use for ASHRAE 90.1-2010 compliant model

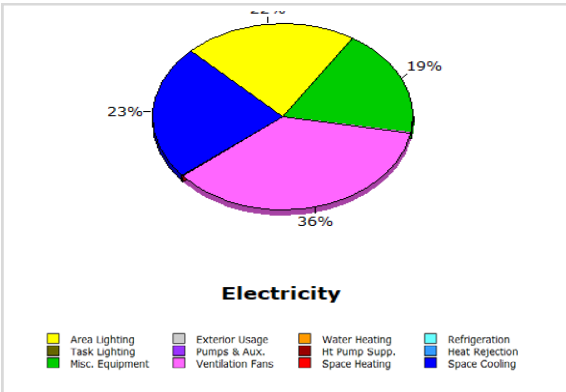

Figure 5Annual Energy Consumption by End-Use for ECBC 2017 compliant model

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OBSERVATIONS

1. The ECBC 2017 compliant EPI is **11.60 kWh/ sq.ft/yr (124.86 kWh/sq.m/yr)** which is lesser than the ASHRAE 90.1 base case EPI is **12.81 kWh/ sq.ft/yr (137.88 kWh/sq.m/yr).**
2. As reflected in the above charts and graphs, ASHRAE 90.1 model consumes significant energy during the winter months, most of which is attributed to heating energy. For the climate of New Delhi, this does seem reasonable for the months of Nov-Feb where heating demand is evident. In comparison, the ECBC 2017 model does not consume significant heating during those months, which, to some extent, can be attributed to its highly efficient envelope.

Table 11: Minimum energy performance requirement

Rating System	Reference Standard / Code	Minimum Compliance Requirements for building in consideration
IGBC	ECBC 2007 / ASHRAE 90.1 - 2010	Meet performance requirements as per ECBC 2007 or ASHRAE 90.1-2010
GRIHA	ECBC 2007	Meet an EPI of 90 kWh/sq.m/year **(8.36 kWh/sq.ft./year)** for commercial buildings in composite climate zone (for HVAC loads only)
LEED	ASHRAE 90.1 - 2010	5% improvement over ASHRAE 90.1-2010 performance, which gives an EPI of **12.17 kWh/sq.ft./year**

3. Modeled building (as per ECBC 2017) achieves an EPI of **82.77 kWh/sq.m./year (7.69 kWh/sq.ft./year)**, which is 8% stringent (for HVAC loads only) and meets the GRIHA requirement.

NOTE

Referring a study from CEPT University & Shakti Foundation, titled Impact of ECBC on building energy consumption at city level, Phase 3, Table 4 - EPI Comparisons, it is evident that ECBC 2017 is 6.58% stringent than ECBC 2007. Considering this, the EPI for ECBC 2007 can be estimated as:

ECBC Version	EPI (kWh/sq.ft./year)
ECBC 2007	12.36
ECBC 2017	11.60

Similarly, Referring the publication from PNNL, it is seen that ASHRAE 90.1-2013 is stringent than v2010 by 7.5%, whereas v2016 is stringent than v2013 by 6.8%. Accordingly, the EPIs can be estimated as below:

ASHRAE 90.1 Version	EPI (kWh/sq.ft./year)
ASHRAE 90.1 - 2010	12.81
ASHRAE 90.1 - 2013	11.85
ASHRAE 90.1 - 2016	11.04

CONCLUSION

For the minimum compliance, the enegy consumption for HVAC, lighting and equipment estimated for the case study for three ratings is as follows:
LEED BD+C V4 = **12.17 kWh/sq.ft/yr**
GRIHA V 2015 = **12.36 kWh/sq.ft./yr**
IGBC Green NB = **12.81 kWh/sq.ft/yr**
It is hence concluded that the minimum energy performance of LEED V4 is most stringent, GRIHA 2015 is is the second most stringent while IGBC is least stringent. **Although, it must be noted that the EPI numbers achieved are only marginally different**.

Although, LEED and IGBC both compare energy consumption with the ASHRAE 90.1 benchmark, LEED is more stringent as it demands minimum 5% reduction from the basecase. Even the maximum reduction from the ASHRAE 90.1 benchmark is 34% in IGBC which goes upto 50% in LEED.

Further, LEED and IGBC projects express the energy cost savings in percentage and do not actually define the energy consumption in kWh. On the other hand, GRIHA projects clearly define the percentage reduction from benchmark as well as the EPI number in kWh/m^2/yr. Moreover, GRIHA EPI is calculated only for HVAC load and excludes all other loads. The above differences make it difficult to compare energy efficiency of LEED & IGBC projects with GRIHA projects in the real life scenario.

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INTEGRATED DESIGN & RETROFIT APPROACH FOR A SMALL COMMERCIAL OFFICE: AEEE OFFICE CASE STUDY

Deepak Tewari[1], Srishti Sharma[2], Satish Kumar[3]

[1]*Alliance for an Energy Efficient Economy*
Delhi, India
deepak@aeee.in

[2]*Alliance for an Energy Efficient Economy*
Delhi, India
srishti@aeee.in

[3]*Alliance for an Energy Efficient Economy*
Delhi, India
satish@aeee.in

ABSTRACT

The cities in India are seeing huge growth in the demand for commercial office spaces which is leading to an unsustainable peak electricity demand largely due to electricity use in cooling, lighting and appliances. The commercial building sector accounts for 9% of the total electricity consumption in India, which is expected to increase further in the coming years. It therefore, requires immediate interventions towards energy efficiency and sustainability in the built environment. The paper presents the case study of design & retrofit in a small commercial office, registered under LEED Interior Design and Construction (LEED V4 ID+C: Commercial Interiors). It provides an overview of an integrated design & retrofit approach for an existing small commercial office located in composite climate of India. The paper lays out the design approach, state of the art technologies, and techno-economic analysis of the office over the conventionally built design. The analysis on energy performance, occupant comfort, end-use monitoring, energy impact of ventilation and challenges faced has been discussed. The methodology adopted for the design & retrofit of this office can be extended to the other commercial retrofit projects of similar size for the development of a rational approach.

Keywords—Energy Efficiency, LEED ID+C, Sustainability

INTRODUCTION

The building sector in India is the second-highest consumer of electricity after Industries and accounts for nearly 33% of the total electricity consumption, of which the commercial sector accounts for 9% and domestic sector has a share of 24% (MoSPI 2019).

The rapid rate of urbanisation is leading to tremendous growth in the commercial floor space and consequently to a huge demand for electricity largely due to growing usage of air-conditioning, appliances and other equipment. Moreover, the uncontrolled urbanisation is also causing environmental degradation, leading to many problems like excessive air pollution, water scarcity, water quality, health impacts and problems of waste disposal.

To address this increasing energy demand in the commercial built environment, Government of India launched the Energy Conservation Building Code. However, the code does not cover smaller commercial buildings that have load limits less than 100 kW (connected load) or 120 kVA (contract demand). It is therefore, an urgent need to develop design guidelines for energy efficiency in smaller commercial buildings as well.

The environmental rating programs such as LEED, IGBC and GRIHA covers overall sustainability features of a built environment comprising of key aspects such as location & transportation, energy & water efficiency, resource management (material & waste) and indoor environmental quality. However, the adoption of these rating programs in small offices is comparatively less as compared to large offices because of low awareness among these consumers. Small office owners tend to focus on achieving equipment level efficiency without considering the holistic system-based approaches where the potential for energy savings is far higher than what they normally would achieve. Due to this lack of awareness on system interdependencies and latest technologies the integrated energy efficiency design approach is often considered as a costly affair, which is not the case.

This paper provides an overview of the integrated design approach for energy efficiency in a small size office by showcasing a real case study of Alliance for an Energy Efficient Economy's (AEEE's) country office. It lays out design approach, system optimisation, state of the art technologies, and techno-economic analysis of the office over a conventional design for creating awareness of building owners of similar kind offices. It also shares insights on energy performance, healthy work environment, and making energy visible for energy management to enable replication of such examples.

METHODOLOGY

The integrated design is a comprehensive holistic approach to design which brings together specialisms usually considered separately. It is complex philosophy that requires holistic and multi-disciplinary interventions to realise the overall sustainability goals.

The integrated design approach adopted in this project aimed to bring together building owner and different specialists like architects, engineers (mechanical, electrical & plumbing), sustainability professionals, and interior designer together to design and implement a high performance environmentally sustainable office within the strict budget and time constraint. The approach is inclusive of the multiple aspects as follows-

1. Open and effective communication between the design, and construction team to bring together unique ideas to develop a whole system thinking approach that allows for full optimization. It is important that all the stakeholders involved are aware of the project vision, objectives and outcomes to benefit the project from individuals' contribution.

2. The design strategies are intertwined together to embrace lean, mean, green philosophy. The envelope optimisation intervention is coupled with the design of energy efficient equipment's and further meeting the energy requirements with green power.

3. Integration of active air-conditioning with air-cooling system for realising the energy performance optimisation to deliver the required cooling. The system is designed on adaptive thermal comfort principles for a wider range of temperature conditions.

4. System level integrated design by pairing the outdoor air ventilation system with the indoor units of variable refrigerant flow (VRF) system, to deliver treated outdoor air during occupied hours.

5. Integration of energy efficient design considerations with the resource efficiency and sustainability features (like LEED rating) for an improved design. The Lean, Mean and Green philosophy was followed by the principles of sustainability to improve the overall energy & environmental performance of the office.

Effective Communication

Effective communication is imperative to an integrated design approach. An awareness session was organised for the design/ construction team to familiarize them about the integrated design approach and system interdependencies. The project vision and goals were communicated to each team to work together in a collaborative manner and design optimized solutions.

Lean, Mean, Green

The *Lean* aims at reducing heat gains inside the building, *Mean* implies using energy efficient state of the art technologies, and *Green* focuses on supplying the remaining energy requirement of the building from renewable sources to minimise carbon emissions.

Lean: Envelope Optimisation: The envelope is an important element of the energy system for improving the overall energy performance of building. In this office, the exterior façade was already built, and therefore only external windows were retrofitted with double glazed glass windows to reduce the solar heat gain and maximise daylight inside the office.

Mean: Energy Optimisation- The energy systems installed in the office are state-of-the-art energy efficient technologies in lighting, air-conditioning, ventilation and energy data management. The details are provided in the next section.

Green: Use of Renewable Power – The energy requirement of the office is offset through the purchase of renewable power in the form of renewable energy certificates (RECs) from independent power producers.

Sustainability principles

To effectively address the environmental sustainability aspects, the office has opted for LEED rating for Interior Design & Construction (LEED V4 ID+C: Commercial Interiors). The approach to energy efficiency and sustainability integrates design, construction and operation aspects to maximise occupant health, productivity, comfort; minimise

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resources like energy, water, waste; to reduce the negative environmental impact. The key aspects of the overall approach are as follows –

Site Selection: The key considerations for the site selection was the accessibility to public transport like a bus or metro train service allowing more people to make use of public transit for daily commute.

Space Optimisation – The office layout was designed to optimise space utilisation for productivity & efficiency of employees. The key considerations were-zoning of work areas, planning visitor spaces and facilities, open and flexible work areas, availability of natural light, external view from each working space, and ergonomics etc.

Resource Optimisation – The old wooden laminated flooring was reclaimed and utilized in regularly occupied spaces of the office to achieve material optimisation. Additionally, low flow flush, faucets, and fixtures have been installed to optimise freshwater usage.

Waste Management – The construction and demolition waste which was generated at the site was reused in the office instead of diverting it to the landfill. Moreover, during the office operation stage, an eight-bin system has been set-up for segregating glass, paper, cardboard, metal, plastic, batteries, e-waste, and organic (wet) waste.

Therefore, this integration of the ideas and design disciplines of each team along with the philosophy of Lean, Mean and Green, followed by the principles of sustainability is called as an integrated design approach leading to an energy efficient' thermally, visually and acoustically comfortable workspace.

CASE STUDY

Alliance for an Energy Efficient Economy's (AEEE) office project scope included renovations in the ground floor of the building. The scope covers demolition and construction of new partitions, ceilings, windows, general finish upgrades as part of the total renovation of existing office. The work also included lighting, electrical and mechanical system design & installation to support the new office spaces. The project details are as follows-

Table 1-Project details of AEEE office

Name	Alliance for an Energy Efficient Economy (AEEE) - Office
Location	New Delhi
Climate	Composite
Nature of the project	Designing-Retrofitting of an existing small commercial office
Rating system	LEED V4 ID+C: Commercial Interiors
Built Up Area	337 sq.m.
Air-Conditioned Area	284 sq.m.
External Glazing area	57 sq.m.
Energy Performance Index	95 kWh/m2/year (Simulation)

SYSTEM DESIGN & TECHNOLOGY USED

The project goal was to create high performance office spaces that optimize energy and the indoor environment, reduce resource consumption, and increase occupant engagement. The *Lean, Mean, Green* approach adopted by the project team led to the inclusion of system-based design strategies along with the state-of-the-art technologies to meet energy efficiency targets without significant additional cost. The design highlights and technology details for energy efficiency are presented next-

- The external façade of the office is retrofitted with Double Glazed Glass windows. It allows striking the right balance of low heat ingress and high visible light transmittance.

- The electrical distribution of the office is designed on the guidelines of separation of electrical circuits. The purpose is to measure and monitor the specific contributions of separate loads to the overall energy use of the office. The aim is to provide greater transparency on energy consumption and enable decision making.

- Each electrical circuit (end-use) has been installed with a small energy sensor i.e. PowerTag that monitors real-time electrical parameters such as Voltage, Current, Power Factor, Power and Energy Consumption. The PowerTag is a small wireless component which gets easily connected to a circuit breaker and captures all the electrical parameters. The SmartLink is a smart communication system which is wirelessly connected to all the PowerTags, and transfers the data to the BMS server.

- The Building Management System (BMS) is installed in the office helps in monitoring of energy, power, thermal comfort, air quality and ambient parameters from a single location an maintaining a historical log. It also enables equipment control, scheduling, interval data analysis, alarms & notifications and benchmarking.

- The air-conditioning system has been designed keeping in consideration adaptive thermal comfort approach of operating air-conditioning in conjunction with ceiling fans. is the system is designed for an indoor temperature range of 25 +/- 1 deg C. Additionally, a dedicated ventilation system is integrated with VRF to maintain a healthy indoor air environment.
    - VRF System: To meet the air-conditioning requirement highly energy efficient VRF system is installed in the office. The installed capacity is 12 HP with a COP of 3.56 (at AHRI conditions) and ISEER of 6.47 under cooling mode.
    - Ventilation System: A dedicated treated fresh air ventilation system has been installed to maintain a healthy indoor air environment by diluting the indoor CO2 levels and other pollutants. The ventilation system performs filtration and pre-cooling and of outdoor air which is equipped with high efficiency particulate filter (MERV-13 rating) and DX system respectively. The system is designed for an air requirement exceeding 30% of the requirement per ASHRAE Standard 62.1-2010. The system is an open loop that performs pre-cooling and filtration of the outdoor air.
    - Ceiling Fans: Super-efficient ceiling fans that operate on Brushless DC Motor (BLDC) technology is installed in the office. The peak power consumption is 28 Watts (at full speed). The fans operate on 24 V DC, by converting the input voltage of 230 V through an integrated power module.

- The lighting system comprises of LED lamps integrated with occupancy sensors. The occupancy sensor detects the occupant movement and switches the lights off when the spaces are not occupied thus saving electricity. The LED lights have a high luminous efficacy of 110 lm/W.

- The office is installed with proper sensors and instrumentation setup to monitor environmental & thermal comfort parameters, which is also integrated to BMS. Key parameters such as temperature, relative humidity, CO2 are being monitored both in the indoor and outdoor spaces. Future provisions for measuring & monitoring particulate matter (PM 2.5 and PM 10) has also been made available.

TECHNO-ECONOMIC ANALYSIS

The office is installed with several energy efficiency design elements and state-of-the-art technologies which has been elaborated in the above section. The below techno-economic analysis has been carried out to understand the additional cost impacts of energy efficient design features and technologies especially in small size commercial offices.

The objective is to create awareness and provide guidance to building owners of small offices on energy efficient & sustainable design options for built construction. A comparison of design features/ technologies installed in a conventionally built commercial office with the technologies installed at AEEE office is presented next.

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Table 2-Comparison of energy efficiency design features & technologies in conventional and AEEE's energy efficient office

S. No.	Description	Conventional Office	AEEE Office
1	External Glazing	– Float glass pane of nominal thickness 5 mm	– Double Glazed Glass 27 mm thickness (6 mm Glass - 15 mm Argon - 6 mm Glass) – SHG: 0.25; VLT: 40%; U factor: 1.6 W/m2-K
2	Lighting System	– LED lighting	– LED lights integrated with occupancy sensors;
4	Air-Conditioning System	– Design indoor temperature: 24+/-1 °C; – System: Split air-conditioners (BEE 3~5-star rating) – Indian Seasonal Energy Efficiency Ratio (ISEER): 4.5	– Design indoor temperature: 25+/- 1 °C; – System: VRF system; – Indian Seasonal Energy Efficiency Ratio (ISEER): 6.47
3	Circulation Fans	– BEE star rated ceiling fans; – Power rating 50~55 Watt.	– Super-Efficient Ceiling Fan with Brushless Direct Current (BLDC) motor; – Power rating 28 W
4	Electrical Distribution	– Mixed electrical circuitry; – System/component level energy analysis is not possible	– Separation of electrical circuits for each end-use application; – Detailed system/component level diagnostics & provides transparency
5	Metering	– None (Only Utility meter)	– Metering each electrical load; – Smallest sensor i.e. PowerTag and SmartLink (from Schneider Electric) for each circuit breaker
7	Ventilation System	– None	– Dedicated system with designed airflow of 760 CFM (exceeding 30% per ASHRAE 62.1-2010); – Pre-cooling DX system 4 TR rating; – High efficiency particulate filter (MERV-13 rating)
8	Monitoring Environmental parameters	– None	– Real-time monitoring of -Temperature, Relative Humidity, and CO_2 at Indoor and Outdoor level – Integration of these sensors with BMS
9	Building Management System (BMS)	– None	– Customized dashboard to make energy usage visible; – Automation through scheduling; – Real time interval data to identify energy usage anomalies; – System/equipment level data analytics, visualisation and notifications

Based on the above technological assessment, it is very much important to know the cost impact of an energy efficient construction in a small office setup. Therefore, to understand the additional cost of an energy efficient construction, a comparison of actual cost incurred at this office versus construction cost of same office with traditional features has been carried out. The conventional design features of a small office are listed in table 2 above. To calculate the cost of a conventional small office with listed traditional design features certain cost assumptions has been made. These cost assumptions have been taken from CPWD specification document Analysis of rates 2019. The details of cost assumptions are provided below –

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Table 3- Cost assumptions for conventional design features

S. No.	Description	Specification	Cost Assumptions (Conventional Construction)
1	Glazing	Float Glass of 5 mm thickness	INR 1184 per sqm of glazing area
2	LED Lighting System	LED Light Fixtures Type -2x2 fixtures & downlighters	2x2 Fixture: Rs. 2150 /piece; Downlighter: INR 800 /piece
3	Split Air-Conditioning System	BEE 5 star split air-conditioners	INR 30,000 per TR
4	Ceiling Fans	BEE- 5-star rating fans of 1200 mm sweep	INR 2250 per fan

The difference between the actual cost of this office and estimated cost of a conventional office (calculated based on the above cost assumptions) is provided in the table below. This provides an additional cost impact of energy efficient technologies implemented in this office and also applicable for smaller size similar offices.

Cost Increment per square meter (with all EE features listed above)	INR 5567 / sq.m.
Cost Increment per square meter (with all EE features except BMS)	INR 2661 /sq.m.

RESULT & DISCUSSION

The AEEE office case study demonstrates the proof of concept for transforming a traditional space into an energy efficient one. It clearly highlights that existing small offices have several possibilities to integrate state-of-the-art technologies in an integrated design & construction approach. The design principles set out in this office provides unique opportunities and knowledge based to small offices to create a healthy, productive and conducive environment for the occupants. The key takeaways from the above analysis is presented next -

Cost analysis- The cost increment due to implementation of energy efficient design features and technologies in a small office setup lies in the range of Rs. 2661 per sq.m. (without BMS) to Rs 5567 per sq.m. (with a full functional BMS). This is over and above the cost of a conventionally built construction for a similar type of offices.

Energy Performance Index (EPI) - The projected annual energy consumption of the office is 31,856 kWh. It is based on the energy simulation results performed as part of the LEED requirement. The figure 1 shows the monthly trend of projected energy use in the office.

The office has been operational since last three months (Aug, Sep & Oct). It is occupied to its full capacity and all systems are operating within the designed limits. The actual energy consumption of the office has been significantly lesser than the simulation results for these respective months. Figure 1 presents a comparison of actual versus simulated energy consumption for different months in a year.

As the actual annual consumption profile of the office is not available, the energy performance index has been calculated on the simulation numbers. Based on the energy simulation results, the energy performance index of the office is 95 kWh/m2/year, which is 43% less as compared to the energy benchmark of an air-conditioned office building prescribed by Bureau of Energy Efficiency (BEE). As per BEE- 1 star rated office the energy performance index is 165 ~ 190 kWh/m2/year. However, the actual EPI of the AEEE office will be significantly lower than 95 kWh/m2/year, which can be validated only after 12 months of operation.

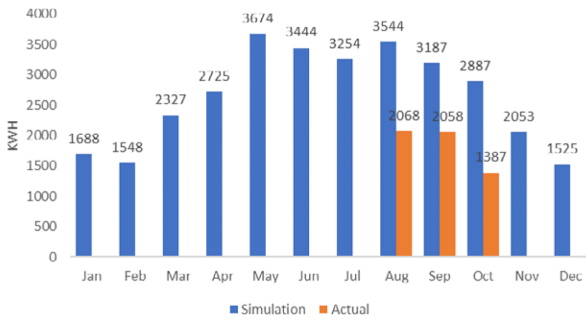

Figure 1: Monthly Electricity Consumption (Actual versus Simulated)

The energy simulation provides greater understanding on the operational end use energy consumption, and also helps know the interactions between different systems to optimize the overall building performance. However, as shown in figure 1 there is a big discrepancy between the simulation results versus the actual i.e. measured energy use. The broader reasons for the uncertainty in the energy simulation results could be due to multiple reasons like - actual occupancy being different from the designed occupancy, difficulty in prediction of human behaviour during building occupancy phase, lack of information on the building envelope properties, and in-built assumptions made in the model.

The specific reasons for the above-mentioned deviation in the energy use is possibly due to following factors-

- As an operating practice the air-conditioning and ceiling fans are always operated simultaneously in the office. Also, the operating temperature setpoint being maintained is 26 ± 1 deg. C which is higher than the designed setpoint.

- The simulation tools are not able to model the part load performance of the BLDC ceiling fans operating at lower speed levels. In the actual operation the fans are operated at the level two speed.

- The office has adequate daylighting during the daytime and occupants prefer to work without artificial lighting.

- The actual occupancy of the office is only 62% of the designed capacity that also remains dynamic throughout the day.

Energy penalty for maintaining a healthy indoor air environment- To maintain a healthy indoor air environment in offices, dedicated ventilation system has become a necessity considering the compromised air quality in many cities in India. However, the operating energy consumption of ventilation system has a significant impact on the overall energy usage of the office. The ventilation alone consumes almost 39% of the total electricity consumption of the office, and second highest after air-conditioning system as shown in figure 2, which is for a particular sample day. However, the energy consumption of ventilation system is dependent on many factors such as – outdoor weather conditions, set-point temperature etc. There is a potential for energy savings by optimising schedules based on occupancy, increasing the setpoint and adjusting the air-flow rate. However, these interventions will be taken up in future.

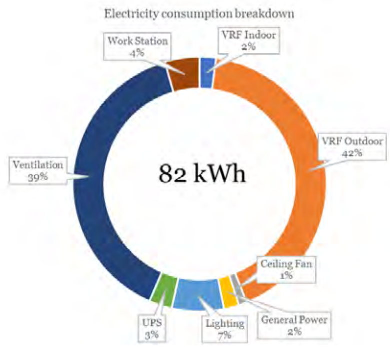

Figure 2: Energy Consumption breakdown (End-Use) for a sample day

Occupant Comfort – The occupant survey was conducted with an intent to get occupant's perception to thermal, acoustical and lighting conditions in their respective workspaces. Additionally, the satisfaction level of occupants in terms of the indoor air quality, cleanliness maintained in their respective workspace as well as in the building, and their overall satisfaction with building performance was also collected. The survey was circulated to all the regular occupants and responses were collected. The results specified that more than 80 per-cent of the surveyed occupants were satisfied with each of the comfort conditions which also compliments the LEED ID+C V4 requirements. The details are presented in figure 3.

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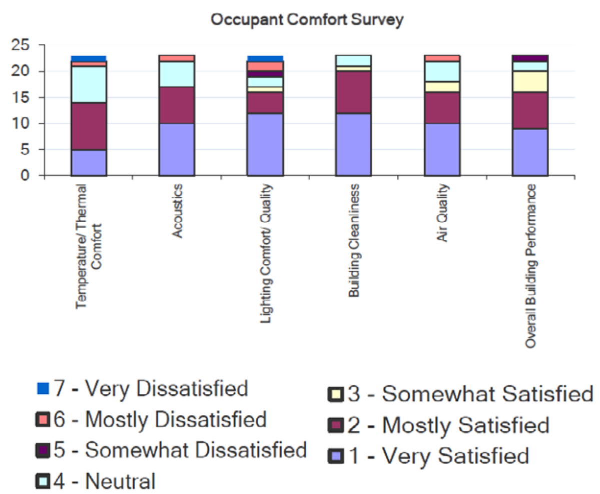

Figure 3: Analysis of Occupant Survey conducted on AEEE's new office employees

Challenges faced – Adopting the philosophy of integrated design approach was not easy and several challenges were faced in the retrofit of this office. Some of these are extensive communication & coordination among the building owner and design teams, non-availability of specific products/technologies in India, longer lead time etc. There is low awareness among the design team on sustainability principles and LEED rating system and therefore required extensive coordination. Some of particular products like specific glazing recommended by the design team were not available in India so an alternate was suggested and this process consumed a substantial time. The ventilation system installed in the office has a significant energy consumption which is an additional cost impact but equally necessary to maintain a healthy indoor air environment.

LEARNINGS & CONCLUSION

The case study presented above provides a deeper understanding of system interdependencies, energy interactions between different systems and cost increment of an integrated design approach especially in a smaller size project.

Close coordination and collaboration between different teams is essential to realise the project goals. The integrated design approach best utilizes the expertise of individuals and brings out unique ideas for innovative and cost-effective solutions.

The end-use energy consumption provides greater insights on the operating performance at different levels. Building /system /equipment level performance can be monitored at a deeper granularity to check for any abnormality and plan the energy saving opportunities. The techno-economic analysis performed in this project provides a generic idea to building owners of similar facilities on overall additional cost impact which could come up over and above a conventional design built. The ventilation system providing excess outdoor air (beyond ASHRAE 62.1-2010 threshold level), and equipped with high filtration efficiency arrests particulate matter (PM10 & PM 2.5) to creates a comfortable environment inside the office. However, the energy impact of the ventilation system is significant.

The approach and the results of the above office case study provides a guiding principle to other offices of similar type to undertake energy efficient design and constructions. The Lean, Mean, Green design philosophy integrated with sustainability principles of green building rating provides a unique approach to create thermally, visually and acoustically comfortable workspaces with a reasonable increment on cost in small size offices.

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ESTIMATING AIR LEAKAGE FOR STAR RATED HOTELS IN AHMEDABAD USING BLOWER DOOR METHOD

Ankit Debnath[1] , Rashmin Damle[1]

[1]*Building Energy Performance*
Faculty of Technology, CEPT University
Ahmedabad, India
eos230@gmail.com
rashmin.damle@cept.ac.in

ABSTRACT

With India's emergence as a global tourism hub, growing awareness of energy efficiency in the hotel industry is becoming an important aspect. The impact of infiltration and its consequent energy consumption in commercial buildings has not received attention in India. Energy audit studies conducted by local agencies and the Energy Department of India shows that hotels have a potential of reducing 20-30% of energy use without compromising hospitality services.

This work studies, air leakage characteristics of 30 air-conditioned double occupancy hotel rooms in Ahmedabad. The studied dataset consists of windows, splits and central AC systems. The leakage characteristics of hotel rooms were tested using blower door method. The measured ACH due to infiltration at 50Pa is normalized to atmospheric pressure conditions, i.e., 4Pa. The normalised ACH is then simulated for the respective geometry to find energy impact and potential financial savings.

This work identifies the correlation between ACH due to infiltration and characteristics like WWR, floor area, air conditioning systems, window frame and tariff. Majority of the rooms were found to be airtight as compared with international standards. Factors such as window perimeter area and type of window i.e., fixed and operable were related directly to the infiltration. Lower window perimeter leads to lower infiltration but at the cost of lesser outdoor view. Low tariffed rooms with split systems were found airtight due to low WWR of 22%. Higher tariffed hotel rooms with centralized system were observed to be airtight. However, these rooms were newly built with bigger floor areas

Keywords— *Airtightness, blower door, hotel rooms, leakage area, ACH, WWR*

1. INTRODUCTION

Best engineering and architectural practice for green building code compliance and meeting international standards includes keeping building construction air tight and maintaining adequate ventilation. In practise, post occupancy air change rates may not meet design intent. Multiple multiple i.e. infiltration/exfiltration from cracks & gaps in the building envelope, change in building construction etc. International studies show significant energy savings potential and reduction in HVAC equipment size by tightening the building envelope. From an energy point of view, it is always favourable to reduce air leakage by tightening the building envelope. However, without a dedicated ventilation system the indoor air pollutant concentration may increase. Infiltration may reduce these concentrations. However, it is not possible to control infiltration/ exfiltration exchanging through building cracks which possibly leads to an unwanted increase in the energy consumption of the building.

Infiltration check for a building envelope can be carried out by two methods, namely steady state pressurization/depressurization i.e., blower door test or dynamic pressurization technique i.e., tracer gas method. The former has been used to comply with international airtight standards like ASTM E-783-93 (1999) and CIBSE TM 23 (2000). Current field result using blower fan method forms the basis of National Institute Bureau of Standards (NIST), U.S. and Air Infiltration and Ventilation Centre (AIVC) databases. The latter is an affordable option and can be applied on a large scale compared to the former.

With a growing awareness of energy efficiency in the hotel industry by the Indian government and hoteliers, energy performance is becoming an increasingly important aspect with India's emergence as a global tourism hub. In the next two to three years after 2014 the hospitality sector is expected to grow exponentially (PWC, 2012) . Energy audit studies conducted by local agencies and the Energy Department of India shows that hotels have a potential of reducing 20-30% of energy use without compromising the quality of hospitality services. The design of a hotel plays a crucial role in cost savings & the emphasis on this aspect is a crucial need. An airtight envelope design can help hoteliers save on energy costs whilst maintaining indoor air quality.

Today, in the business environment, hotels are adopting energy efficient measures. Based on interviews from engineering and service's team conducted by (PWC, 2012), 30% of the leading hotel chains in India responded with a positive answer towards spending more in energy conservation measures over investing in technologies, efficient procurement and staff training. For a study released by Honeywell with research firm IMRB International and Ernst & Young (EY) showed profits form energy conservation measures implemented for hotels in India as well as improvement in three key sustainability parameters of green technologies, safer environment and productivity. Hotels leading in these aspects help patrons in making them comfortable by setting the optimum environment for peace and relaxation through heating, cooling, lighting, etc. Adoption of these measures by market leaders has become a growing trend more due to customer awareness and as a driving factor in the market.

In India, travel and tourism revenue represents 5.2% (PWC, 2012) of the country's annual GDP. The hospitality sector consumes 60% of the resources providing accommodations like hotels, resorts, guesthouses etc. Government of India, classifies hospitality sector as a priority to enable sustainable development in the commercial sector. In Figure 1 shows the energy consumption of commercial sector in India as per Federation of Hotels & Restaurant Association of India (FHRAI). Hospitality services in India is the third highest energy consuming sector with 489 registered hotels. As per 62nd annual report by FHRAI for 2017-18, India has approximately.

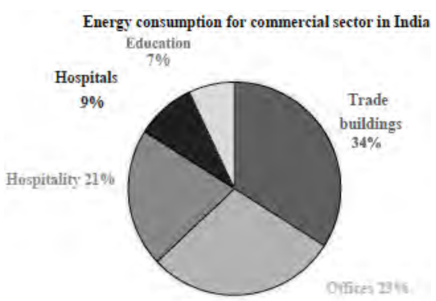

Figure 1 Energy Consumption of India as per FHRAI

For a correctly sized HVAC system complemented with an airtight envelope can reduce cooling demands by 10-20% (Air Conditioning Contractors of America, 2016).

Energy conservation building code (ECBC, 2017), provides measures to seal openings, joints, ducts & fenestrations to reduce air leakage through the building envelope. However, there is no measured data for infiltration rates in hotels. While an earlier study (Bist, 2018) provided data on 23 residential units, this study attempts to fill the gap on infiltration data for the hotel building type. The findings in this research work will potentially represent a comparative analysis of the airtightness values for different parameter of analysis for hotels in Ahmedabad.

2. METHODOLOGY

In this work, blower door method is employed for measuring leakage characteristics of hotels rooms. Tests are carried out as per, ASTM, E1827-96, Standard Test Methods for Determining Airtightness of buildings using an Blower Door (2007). Indoor set point for temperature was taken as 24ºC (ASHRAE, 2017) and assumed COP of 3.6 for both the system type. Split systems were modelled with PTAC system in DesignBuilder (DesignBuilder v.6.1, 2019). VRF centralised system was modelled for seven hotel rooms. ACH obtained for blower door method measurements was input as ACH due to infiltration in simulation. Also, the tests were carried out as under clear sky conditions and wind speed under 2.3 m/s.

All the 30 hotel geometries were simulated in DesignBuilder (DesignBuilder v.6.1, 2019) with the weather file of Ahmedabad. TEC Minneapolis blower door BD3- KIT- 100 at CEPT University has been used for airtightness tests. The research methodology is divided into three major parts namely measurements, calculation and simulation. The flowchart of the research method is shown in Figure 2. The tests were conducted over a period of five months for thirty double occupancy AC hotel rooms in Ahmedabad. Both pressurization and depressurization tests were carried out for all hotel rooms. Pressurization creates a positive pressure in the zone forcing air through the gaps present in the envelope. An opposite airflow for depressurization takes place creating a suction pressure inside the room. Airflow measured by the blower fan is recorded using TEC's free software, TECLOG4. The software normalizes the effective leakage area at 4Pa and 10Pa from the airflow recorded at 50Pa pressure difference as per ASTM E1827-96. Effective leakage area (in^2) for all the rooms were compared with multiple parameters

like WWR, age of construction and tariff to correlate the trends and anomalies with the experimental observations. The final ACH due to infiltration at 4 Pa is calculated using cfm at 50Pa with equation (1)
Simulated models sharing a similar climate, indoor set point, COP of 3.6 (based on market survey), geometry and wall type as measured were designed. Separate analysis was done for rooms with split and centralized systems for baseline (measured ACH) and no infiltration. For the thirty simulated geometries the infiltration load in kWh for peak summer month of Ahmedabad from April to October was taken. For the observed loads the local power tariff for commercial buildings was used to calculate the potential financial saving to understand the impact of airtight envelope.

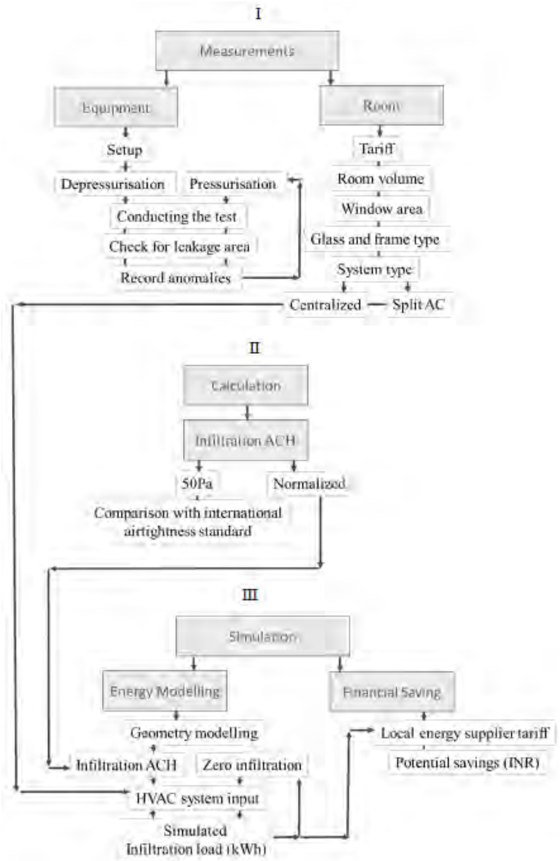

Figure 2 Methodology flow chart

A. DATA COLLECTION APPROACH

1. For investigation in hotel rooms, hotels were contacted individually through their front desk reception, CEPT travel desk and CEPT admin contacts. Appointment was made with the chief engineering officer or the manager who headed the facility services of the building
2. During the appointment, basic understanding was given about importance of airtight hotel rooms & its cost savings potential and a brief walkthrough for non-destructive testing by blower door method.
3. A suitable appointment for testing was set up during the lean periods of occupancy in the hotel. A time limit of maximum two hours was given by the facility team to complete the test before the room could be made operational.
4. To select the sample of hotels to be taken, central limit theorem was used. A sample size of minimum 30 hotel rooms was randomly selected.

B. CALCULATIONS

For the collected data, airflow (in cfm) for pressurization and depressurization, effective leakage area at 4Pa, constant coefficient (C) for individual hotel room were sorted as per the date of tests conducted.
Volume of the room, window to wall area ratio (WWR), wind speed and temperature difference during the measurement for indoor and outdoor temperature T_{in} and T_{out} were sorted as per the date of the test conducted.
Blower door method gives corresponding to a depressurization of 50Pa. Based on the test data and dwellings, mean infiltration rate at 4Pa (atmospheric conditions) is approximately equal to $1/20^{th}$ of the air flow at 4Pa pressure difference as shown in equation 1 (Awbi, 2003)

$$ACH4 = Q_{50} / (20 \times V) \qquad (1)$$

Where,
ACH_4 = air change per hour (h^{-1}) normalized at 4 Pa
Q_{50} = airflow at 50Pa (cfm)
V = volume of the room (m3)

Heat transfer due to infiltration is calculated using equation (2) given by:
Mass flow rate due to infiltration:

$$m_{inf} = density\ of\ air \times (ACH_4 \times V) / 3600 \qquad (2)$$

Where,
m_{inf} = mass transfer due to infiltration (kg/s)

Latent heat transfers due to infiltration is calculated by equation (3):

$$Q_{l,inf} = m_{inf} \times hfg \times (W_o - W_i) \qquad (3)$$

Where,
$Q_{l,inf}$ = latent heat load due to infiltration (W)
hfg = latent heat of vaporization of water (kJ/kg)
W_o = outdoor humidity ratio (kgwater vapour/kgair)
W_i = indoor humidity ratio (kgwater vapour/kgair)

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Sensible heat transfers due to infiltration is calculated by equation (4):

$$Q_{s,inf} = m_{inf} \; x \; cpm \; x \; (T_{out} - T_{in}) \qquad (4)$$

Where,
$Q_{s,inf}$ = sensible heat load due to infiltration (Watts)
cpm = specific heat capacity of the infiltrated air (j/gm °C)
T_{in} = 25°C / 77F at 50% (ASHARE Fundamentals, 2009)
T_{out}= outdoor temperature (°C)

In this work, 30 air conditioned double occupancy hotel rooms in Ahmedabad were studied. Table 2 Characteristics of the studied hotel rooms shows different hotel rooms with their respective characteristics. The table categorises rooms as, 18 rooms with split ACs, 9 rooms with central ACs and 3 rooms with window AC unit. Table 2 shows the year of construction, floor area and window to wall area ratio (WWR) of the hotel rooms. These hotel rooms were tested using blower door method (pressurization/depressurization at 50 Pa) to find out leakage area of individual rooms.

Table 1 Hotel room description

Hotel	Built Year	System Type	Floor Area (m^2)	WWR (%) | Wall area (m^2)
Hotel 1	2018	Centralised	81.8	14 | 30
Hotel 2	2017	Centralised	16.5	57 | 9
Hotel 3	2016	Centralised	22.7	42 | 20
Hotel 4	2016	Centralised	12.0	67 | 8
Hotel 5	2015	Centralised	9.75	17 | 8
Hotel 6	2012	Centralised	26.2	19 | 9
Hotel 7	2011	Centralised	51.8	23 | 19
Hotel 8	2010	Centralised	37.2	24 | 15
Hotel 9	2001	Centralised	8.4	35 | 7
Hotel 10	2009	Window	12.9	13 | 7
Hotel 11	2008	Window	15.1	12 | 9
Hotel 12	1990	Window	22.2	6 | 8
Hotel 13	2017	Split	13.1	61 | 9
Hotel 14	2016	Split	8.9	41 | 8
Hotel 15	2014	Split	11.8	13 | 7
Hotel 16	2013	Split	15.4	30 | 12
Hotel 17	2010	Split	37.4	10 | 13
Hotel 18	2010	Split	13.2	19 | 7
Hotel 19	2010	Split	27.0	10 | 14
Hotel 20	2009	Split	4.6	14| 5
Hotel 21	2009	Split	22.1	9 | 9
Hotel 22	2009	Split	15.0	15 | 7
Hotel 23	2009	Split	18.0	20 |10
Hotel 24	2009	Split	13.0	10 |6
Hotel 25	2008	Split	17.9	10 | 8
Hotel 26	2008	Split	12.0	11 | 6
Hotel 27	2002	Split	44.2	9 | 15
Hotel 28	2001	Split	21.2	11 | 10
Hotel 29	2005	Split	22.8	21 | 14
Hotel 30	1991	Split	8.2	25 | 5

C. OBSERVATION

Airflow difference during depressurization and pressurization at 50 Pa

Results for the pressurization and depressurization tests in 30 hotels studied are shown in Figure 3. It was observed that, percentage difference in air flow between pressurization and depressurization test varied from 1% to 20%. For the measured 27 hotels a mean difference between the two test was found to be 12%. For a study carried out by (Finch, 2009) showed that the difference in pressurization and depressurization values can be up to 25%. Therefore, it can be concluded that experiments in this study were carried out appropriately. Case 1 highlights a hotel room in which it is observed that depressurisation was higher than pressurisation. The reason for the observation that could be, case 1 had a window AC with a loosely attached rubber gasket around the perimeter placed towards the indoor side of the envelope.
Case 2, highlights two hotel rooms as case 2.a and 2.b. It is observed that airflow measured for depressurisation at 50 Pa was negligible/non measurable (below 25 cfm) by the blower fan for both the sub cases. The reason for the above observations could be, in case 2.a., the room had a minimum exposed area with newly assembled aluminium window frame with 74 cfm of airflow measured during pressurization through the washroom door perimeter. Similarly, for case 2.b. air sealed double glazed unit with carpeted washroom entry minimized infiltration giving a non-measurable flow below 25 cfm at 50 Pa pressure difference.

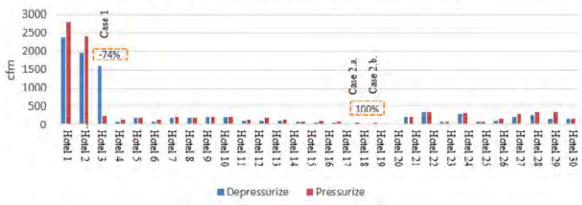

Figure 3 Comparison of measured ACH in different hotels with international standards

D. AIR LEAKAGE FOR NORMS

For the dataset of thirty hotels a comparison of ACH at 50Pa due to infiltration is carried out. Figure 4, shows the comparison with the recommended airtightness for six international standards. It is observed in Figure 4 that 70% of the rooms have airtightness of 0.6 ACH as recommended by PassivHaus. These hotel rooms had a leakage area less than 10in^2 compared to older hotels build before 2010.This observation can be due to, WWR and floor area of the rooms.

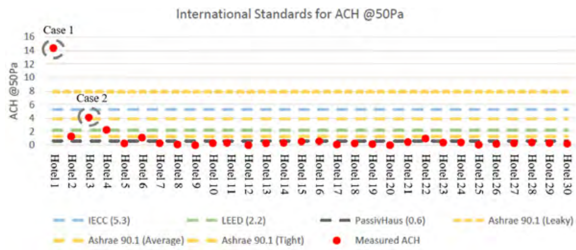

Figure 4 International standard for ACH@50Pa

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E. WINDOWS

In Figure 5, WWR of 20%, 40% and 70% are shown respectively. This helps to understand the variations in the window size with WWR. Energy compliance standard, ECBC (2017) recommends a maximum of 40% WWR for all climatic conditions.

Figure 5 20%, 40% and 70% WWR

It is observed that 50% of the casement windows (blue dots) have a WWR between 10% to 20%, amongst which 85% of them have a leakage area of less than 12in^2. These hotels were typically below the three-star rating. Similarly, for three and four stared hotels with fixed non-operable windows (yellow dots) it is observed that 87% of the hotel rooms have a leakage area below 10in^2. The reason for the above two observations could be rooms having fixed window frames. In general, it is observed that three and four star hotels have a higher WWR of 21% and 45% respectively and lower leakge rate of 13 and 10 in^2 respectively due to better construction quality and practices.

Figure 6 highlights three cases for sliding windows. The three cases are, case 1 showing leakage area above 15 in^2 for less than 15% WWR in four rooms, case 2 showing leakage area between 10-15 in^2 for 20% WWR in two rooms and case 3 showing leakage area of 4.5 in^2 for 35% WWR in one room. These observations can be explained by considering their construction quality and condition. In case 1 for all four rooms, locking rubber gasket in the sliding track of the window frame was absent. Two rooms in case 2 were built before 2010, which shows the effect of weathering on window frame seal as the same was observed during experimentation. Case 3 hotel room built in 2016, had a newly installed window frame with rubber gaskets on window as well as floor carpet flushed washrooms doors resulting in minimum leakage area of 4.5 in^2.

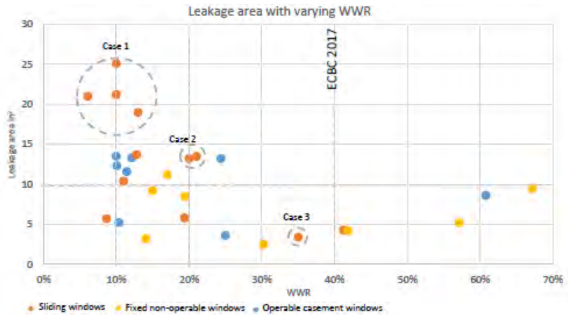

Figure 6 Leakage area for varying WWR

Figure 7 shows leakage area (in^2) against respective hotel floor area (m^2). It is observed that the leakage varies from 4.5 in^2 to 20 in^2. The figure highlights three groups of cases. Case 1 shows hotel rooms having a mean floor area of 16 m^2. Case 2 shows the decrease in leakage area with the increase in floor area. Case 3 shows the biggest room with minimum leakage area.

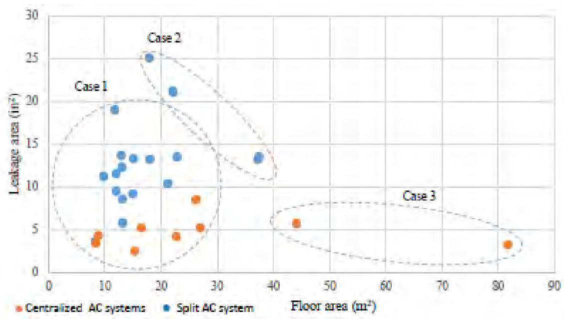

Figure 7 Normalized comparative analysis for leakage area varying with floor area

Case 1, highlights rooms with nine out of eighteen rooms have split AC systems. It was observed that most of these rooms have a leakage area above 10 in^2. The source of leakage was observed due to negligence in installing window sealing, absence of rubber gaskets on the slider track of window, unfit/damaged washroom door and inefficient/second hand indoor AC models. Similarly, in case 2 hotel rooms with split systems have a leakage area above 10 in^2. The highlighted cases show a decreasing trend in leakage area with respect to increase in floor area. The same can be observed in case 3. These are the two largest room with a centralized system. Thus, highlighted hotels for all the cases with centralized system are four star hotels which have a bigger floor area with tighter envelope.

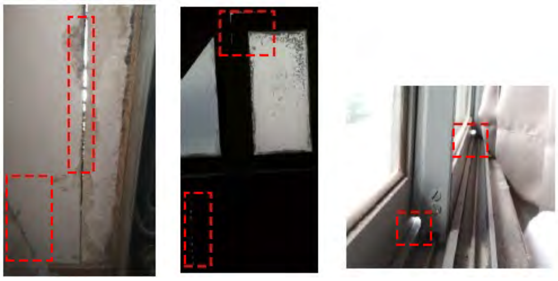

Figure 8 Leakage pathways through window perimeter

Figure 8 shows unsealed gaps that form around the perimeter zone of the window unit after installation. Lack in periodic maintenance and weathering gradually had further caused cracks on the adjoining wall creating pathways for infiltration through the envelope. Absence of rubber gaskets in the window slide track was a common practice in hotels. Similarly, Figure 9 shows defective installation, absence of locking rubber gasket in bathroom door brackets and damaged corners. These gaps showed some common source of infiltration in the hotel rooms

Figure 9 Leakage pathway through washroom doors

F. AGE OF CONSTRCTION

Figure 10 shows leakage in hotel rooms chronologically for two window frame type. It was observed that, 43% of the hotel rooms in the studied dataset were built in the past ten years. These hotel rooms had a leakage area less than 10 in^2 compared to older hotels build before 2010.

Figure 10 for year of construction of hotel with the leakage area in in^2

Rooms built in between 2005 – 2010 with operable windows had a mean leakage area of 13 in^2. Rooms with leakage area above 15 in^2 were due to gaps in the envelopes shown in Figure 8 and Figure 9. Figure 10 shows only two rooms built around the 1990 with different leakage characteristics. Hotel room 1 with a smaller WWR than hotel 2 shown in Figure 10 representing the tighter room as highlighted.

Hotel 1 built in the early 90's shows an effective leakage area of 21 in^2 due to gaps around the exposed wooden window frame for a casement window. Hotel 2 is a similar room in a different hotel, with similar construction type, built year and a higher WWR of 19% more than hotel 1. Hotel 2 with a leakage area of around 3.6 in^2 making it tighter than newer built rooms. This can be due to aluminum window frame with sealed slider tracks and elevated washroom door from the floor area.

G. TARIFF

Tariff of double occupancy air conditioned hotel was 850 INR to 4600 INR. In general, one and two star hotels were 1500 INR and accounted for 43 % of the hotels studied. Three and four-star hotel tariff varied between 2200 INR and 4600 INR and accounted for 37 % and 20 % respectively. One third of the total hotel rooms was observed to have a mean leakage area of 13.5 in$_2$ ranging between 880 INR - 2200 INR. Similarly, hotel rooms beyond the 2000 INR range had an airtight envelope and centralized system. The airtightness of the hotel rooms was maybe due to, age of the building (built after 2010) with fixed glazing windows for most of the cases. Highlighted case shows a varying leakage area for spilt AC hotel rooms with a similar tariff of 1000 INR. The highlighted cases, show variation in leakage area maybe be due to the size of exposed area. Hotel rooms with minimum WWR have an airtight envelope compared to rooms with larger WWR for the same tariff and system type.

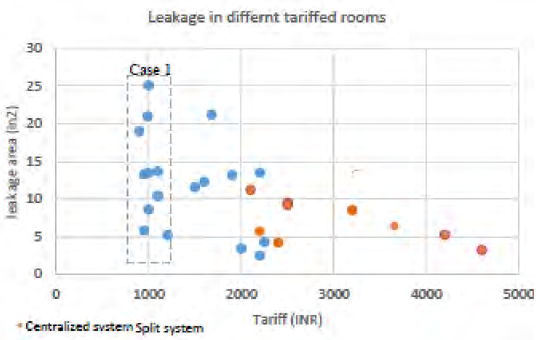

Figure 11 Leakage in different tariffed rooms

DesignBuilder (DesignBuilder v.6, 2018) software was employed for simulating the hotel geometries with the infiltration values obtained from the blower door experiment. Figure 12 Simulated infiltration energyshows the total energy consumption only due to exterior infiltration in the thirty simulated cases for the two different system type i.e., split and centralized. The energy consumption was recorded for cooling period from April to October. Similarly, for split systems rooms with higher infiltration with gaps in frames, weathered or without sealing show high energy consumption. Hence the rooms are airtight by having minimum exposed area to the exeriror .

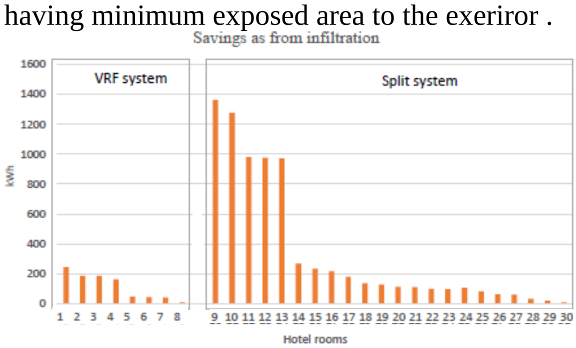

Figure 12 Simulated infiltration energy

A similar trend for potential financial savings can be seen for split and centralized systems in Figure 13. Hotel room with split systems, from 10 to 31 has the maximum financial saving potential of 6,135 INR during the seven months. Similarly, hotel room with centralized systems, from 1 to 8 has the maximum financial saving potential of 1,094 INR during the seven months.

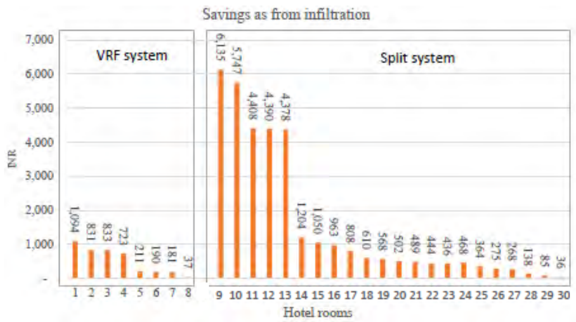

Figure 13 Potential financial savings from simulated cases

5. CONCLUSION

In this study air leakage characteristics of 30 commercial buildings (hotel room) in Ahmedabad have been studied using blower door method. The objective of this study is focused on correlating the measured infiltration rates with international ACH standards, envelope characteristics, leakage pathways and quantifying the energy penalty due to infiltration. The work was able to identify the correlation between ACH due to infiltration and multiple varying envelope characteristics like WWR, floor area, HVAC systems, window frame and tariff.

The comparative study of ACH for different floor areas showed 70% of the rooms had airtightness of 0.6 ACH as recommended by PassivHaus. Amongst the five other international standards compared PassivHaus is the most stringent. Hotel rooms without a dedicated fresh air supply can have poor indoor air quality. This occurs mainly in the split air conditioned system where the CO_2 concentration increases over the duration.

For the measured 27 hotels a mean difference between the two test i.e., pressurization and depressurization was found to be 12%. This showed the tests conducted were done appropriately for the hotel rooms.

Hotel rooms with two types of windows i.e., fixed and operable were predominantly seen. 85% of the casement windows with a WWR of 10% - 20% had a leakage area greater than 12in^2. Whereas, fixed windows in Figure 15 show that they are more effective in minimizing infiltration than sliding or casement window frames. Hence, hotel rooms without compromising on the outdoor view can build an airtight envelope by opting the correct type of window frame. However, opting for fixed windows with larger WWR can lead to increased heat gains.

Newly installed window frame with rubber gaskets and floor flushed washroom doors measured a minimum leakage area of 4.5 in^2.

Airtight envelopes were mostly seen in hotel room with a tariff more than 2000 INR having a floor area greater than 20m^2. These rooms had an outdoor view with a WWR from 30% - 70% with a leakage area less than 15 in^2. Rooms above 2000 INR range mostly had fixed glazing rooms. These were four star rooms with a mean leakage area of 5.6in^2 and WWR of 45%. These were newly built rooms built after 2012 which may have used good quality of construction material to achieve an airtight envelope. For the studied dataset, 43% of these hotel rooms were built in the past ten years achieving a leakage area of less than 10 in^2 compared to older built hotels. Similarly, rooms built in between 2005 – 2010 with operable windows had a mean leakage area of 13 in^2. The three star rooms built between 2005- 2011 had a mean leakage area of 10.2 in^2 and 21% WWR. Similarly, two star and below

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rooms had an average area leakage of 16.5 in^2 and 18% WWR

In this study a mean effective leakage area of 7in^2 for centralized systems and 20in^2 for split systems were found. Construction with split systems could be leaky due due to the design decision of getting the fresh air through uncontrolled infiltration. However, a too tight or leaky envelope will lead to poor air quality and energy wastage repectively. In case of centralised systems, with dedicated fresh air provisions, any infiltration adversely effects the energy consumption. Therefore, any case of infiltration is a source of energy penalty for the hoteliers in a centralized conditioned room. From the simulation, it was found that, Hotel room with split systems, had a maximum financial saving potential of 6,135 INR and 1,094 INR for centralized systems during the seven months. This shows the potential financial saving for one room. However, in a hotel, rooms with similar infiltration characteristics can scale up the potential financial savings.

Finally, based on the field observation and good practices observed during measurements, certain measures can be advised to maintain an airtight envelope:

1. Using silica gel or rubber gaskets to seal gaps,
2. Flushed washroom doors,
3. Sealed window knobs in casement windows.
4. Retrofitting old weathered window frames,
5. Sealing under gaps left after window ac unit installation,
6. Gaps left out between the sliding window panes and

these above measures for air-conditioned space when implemented can minimize the ACH due to infiltration rate further improving the indoor air quality and acoustics. Radiant cooling could be a good option if humidity control can be actually achieved due to tight façades.

NOMENCLATURE

ACH: Air change rate (h^{-1})
ACH_{50}: Air change rate (h^{-1}) at 50 Pa
ACH_4: Air change rate (h^{-1}) at 4 Pa
ELA: Effective Leakage area (in^2)
ELA_4: Effective Leakage area normalized at 4 pascal (in^2)
NL: Normalized Leakage
Qs,inf: Sensible heat transfer due to infiltration (W)
Ql,inf : Latent heat transfer of infiltration (W)
Q50: Airflow at 50Pa difference (cfm)
C: Specific heat capacity of infiltrated air (kJ/kg.K)
wv: Water vapour
da: Dry air
CO_2: Carbon dioxide
PPM: Parts per million
PassivHaus: Passive House Institute
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

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ASSESSING THERMAL PERFORMANCE OF BUILDING ENVELOPE OF NEW RESIDENTIAL BUILDINGS USING RETV

Prashant Bhanware[1], Vasudha Sunger[1], Sameer Maithel[1]

[1]*Greentech Knowledge Solutions Pvt. Ltd., India (Indo-Swiss Building Energy Efficiency Project)*
New Delhi, India
pmtu@beepindia.org

ABSTRACT

Recently launched Eco Niwas Samhita 2018 or Energy Conservation Building Code for residential buildings uses a parameter called Residential Envelope Transmittance Value (RETV) to define thermal performance of the building envelope (excluding roof) for the cooling dominated climates. RETV provides a quantitative measure of the average heat gains over the cooling period through the building envelope. The code defines a maximum RETV value of 15 W/m^2.

This paper presents evaluation of RETV of sample residential projects located in composite (Noida, Mohali) and warm-humid (Chennai, Pune and Thane) climate regions. The methodology consisted of collecting construction drawings, door-window schedule and construction details from the builders, calculation of RETV as per the method prescribed in Eco-Niwas Samhita and evaluating RETV compliance.

The study covers both individual and multi storey apartments. The Window-to-wall ratio (WWR) of the sample projects range from 12% to 41%; while window-to-floor area ratio range from 7% to 25%. The sample projects covers a variety of walling materials: monolithic concrete walls, AAC blocks, Fly ash bricks and brick cavity walls. The RETV of the projects was found to vary from 7 W/m^2 to 24.5 W/m^2. The analysis show that proper choice of walling material and optimum design of shading of windows is critical in meeting RETV compliance.

Keywords—Eco Niwas Samhita, Thermal performance, Building envelope, Residential Envelope Transmittance Value, Heat gain

INTRODUCTION

As per the GBPN report (Rajan Rawal *et al.*, 2014) the residential buildings are expected to increase by 2-fold in terms of floor area by 2030. In terms of electricity consumption, residential buildings consumed 255 TWh electricity in 2017 which is estimated to multiply by more than 3 times and reach to 850 TWh by 2030 (NITI Aayog, 2015). Increased used of decentralised air conditioning units in households to achieve thermal comfort is the prime reason contributing to increase in electricty consumption (BEE, 2018).

In India, most parts have cooling-dominated climate.The indoor temperatures (thermal comfort) and sensible cooling demand is heavily influenced by the building envelope design. It is critical that the new residential buildings have better quality of building envelope.

ECO-NIWAS SAMHITA 2018

The new Eco-Niwas Samhita 2018 (Part 1:Building Envelope) sets minimum building envelope performance standards (BEE, 2018). It has the following provisions:

1. To minimize the heat gain in cooling dominated climate or heat loss in heating dominated climate;
   - Through the building envelope (excluding roof):
     a. It uses a parameter called Residential Envelope Transmittance Value (RETV) to define thermal performance of the building envelope (excluding roof) for the cooling dominated climates (Composite Climate, Hot-Dry

Climate, Warm-Humid Climate, and Temperate Climate)

b. Maximum U-value for the cold climate

- Through the Roof: Maximum U-value for Roof

2. For natural ventilation potential
    - Minimum openable window-to-floor area ratio with respect to the climatic zone
3. For daylight potential
    - Minimum visible light transmittance with respect to window-to-wall ratio

The code focuses on building envelope and aims to improve the thermal comfort and reduce the energy required for cooling and lighting in new dwellings.

The present study assesses the thermal performance of building envelope of eight new residential projects located in Warm and Humid and Composite climates zones of India using Eco Niwas Samhita code provisions. This involves calculation of RETV (Equation 1), U_{roof} and drawing inferences on the factors that influence them.

The selection of projects have not been done as per any scientific sampling technique. The objective while selecting these residential projects was to highlight RETV results with varied walling and roofing construction materials and different storeyed (low-rise, mid-rise and high-rise) buildings. Based on this criteria, some builders were approached to provide the required information voluntarily. The analysis of these projects is presented in this paper.

METHODOLOGY

The assessment of sample residential projects was conducted using the following steps-

DATA COLLECTION

Architectural drawings, door-window schedule and construction details for wall, roof and glass specifications were collected from the builders.

BUILDING ANALYSIS

Each of the block was analysed for the climate type, orientation, location, carpet area, number of dwelling units, type of dwelling units, height of the block, opening area, WWR, shading devices and material construction details.

CALCULATING THE RETV FOR SAMPLE RESIDENTIAL PROJECTS

RETV is the net heat gain rate (over the cooling period) through the building envelope (excluding roof) of the dwelling units divided by the area of the building envelope (excluding roof) of the dwelling units (BEE, 2018).

Equation 1: Equation to calculate RETV

$$RETV = \frac{1}{A_{envelope}} \left[\underbrace{\left\{ a \times \sum_{i=1}^{n} \left(A_{opaque_i} \times U_{opaque_i} \times \omega_i \right) \right\}}_{\text{Term I}} + \underbrace{\left\{ b \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times U_{non-opaque_i} \times \omega_i \right) \right\}}_{\text{Term II}} + \underbrace{\left\{ c \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times SHGC_{eq_i} \times \omega_i \right) \right\}}_{\text{Term III}} \right]$$

- $A_{envelope}$: envelope area (excluding roof) of dwelling units (m^2). It is the gross external wall area (includes the area of the walls and the openings such as windows and doors).
- A_{opaque}: areas of different opaque building envelope components (m^2)
- U_{opaque}: thermal transmittance values of different opaque building envelope components ($W/m^2.K$)
- $A_{non\text{-}opaque}$: areas of different non-opaque building envelope components (m^2)
- $U_{non\text{-}opaque}$: thermal transmittance values of different non-opaque building envelope components ($W/m^2.K$)
- $SHGC_{eqi}$: equivalent solar heat gain coefficient values of different non-opaque building envelope components
- ω_i: orientation factor of respective opaque and non-opaque building envelope components; it is a measure of the amount of direct and diffused solar radiation that is received on the vertical surface in a specific orientation.
- U_{wall}: U- value of walling material in $W/m^2.K$
- U_{roof}: U- value of roofing material in $W/m^2.K$
- U_{glass}: U-value of glass material in $W/m^2.K$
- $SHGC_{equivalent}$ (Weighted average value) : SHGC Equivalent is the SHGC for a non-opaque component with a permanent external shading projection. It is calculated by multiplying the External Shading Factor (ESF) with the SHGC of unshaded non-opaque component.

As per the code provision, the RETV of the building envelope (except roof) for four climate zones: Composite, Warm-Humid, Hot-Dry and Temperate should not be more than 15 W/m^2.K for RETV compliance.

As per the code provision, to comply for roof, the U-value of roof should be less that 1.2 W/m^2.K.

The calculation requires thermal properties, shading, areas and orientation of building envelope components. Where,

- RETV equation has three terms – Term I, Term II and Term III.
- To calculate Term I, U value of the wall construction material is calculated (thermal conductivity is required), envelope lengths and height of the tower are measured from the architectural drawing.
- For Term II, window areas are referred from the door window schedule drawing and glass specifications is referred from the material test certificate.
- For Term III, H and V values are measured for shading devices overhang and side fin from the architectural dwawings (Figure 1,Figure 2)

CALCULATING THE U_{roof} FOR SAMPLE RESIDENTIAL PROJECTS

The U_{roof} of the roof assembly was calculated using the information on roof construction and thermal properties of various materials used for roof construction.

ASSESSING THE THERMAL PERFORMANCE ON THE BASIS OF RETV & U_{roof} RESULTS

The thermal performance of the sample residentials projects is evaluated by studying the impact of different design decisions on RETV.

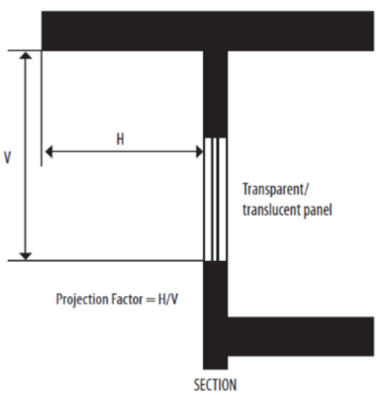

Figure 1:Measuring H and V values for overhang (section)

RESULTS AND ANALYSIS

Table 1 presents:

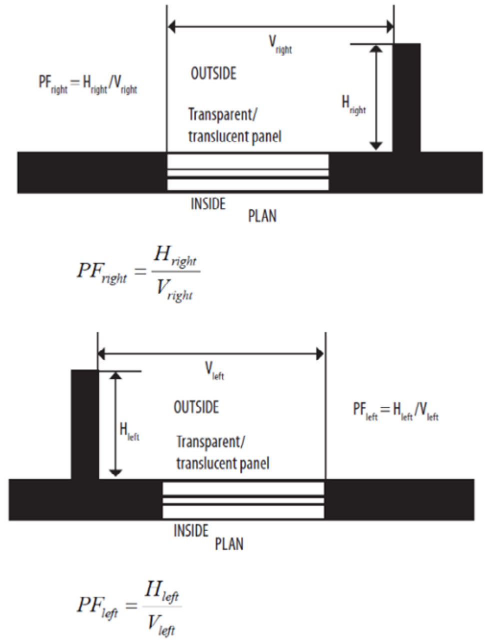

Figure 2:Measuring H and V values for side fin (left and right) in plan

- Project Details (Orientation, Location and no. of storeys)
- Construction Details (Walling, roofing and glass details)
- Results (WWR, $SHGC_{equivalent}$ and RETV)

The residential projects are located in Warm & Humid and Composite climate zones (Figure 3). The height varies from 2 to 26 storeys. The architectural details of the projects are provided in the annexure. The projects have walling of different types such as Monolithic concrete, AAC Blocks, Fly ash brick, Industrial slag brick and Brick cavity walls. The WWR(%) lies in the range of 12.6 to 41.3%. The RETV varies from 7 to 24.5 W/m^2.

* *The cost calculations are done as per CPWD DSR 2018. The rates are likely to vary significantly across the country.*

Table 1: Project wise U_{roof} and RETV results

	Project Details			Construction Details			Results		
	Orientation	Location	No. of storeys	Walling details	Roofing details	Glass details	WWR (%)	SHGC$_{eq}$	**RETV** W/m^2
Project 1	Longer sides face E-W orientation	Chennai	19-storey	15mm Plaster (External); 170mm Monolithic concrete wall, 10mm Plaster (Internal) **U_{wall}=3.20 W/m^2.K**	15mm Plaster (External)+150mm RCC+10mm Plaster, **U_{roof}= 3.3 W/m^2.K**	6mm Single clear glass, U_{glass}=5.7 W/m^2.K, SHGC=0.83	17%	0.54	**21.1**
Project 2	Longer sides face N-S orientation	Chennai	4-storey	20mm Plaster (external); 200mm Monolithic concrete wall; 15mm Plaster (Internal), **U_{wall}=3.0 W/m^2.K**	40mm white reflective tile; 50 mm mud phuska; Brick Bat Coba; 120 mm RCC; 10 mm (interior plaster), **U_{roof}= 1.86 W/m^2.K**	6mm Single reflective glass, U_{glass}=5.8 W/m^2.K, SHGC=0.59	19.3%	0.46	**17.5**
Project 3	Longer sides are orienting towards NW-SE	Chennai	2-storey	15 mm Exterior plaster; 230mm Industrial Slag Brick; 10mm Interior plaster, **U_{wall}=0.93 W/m^2.K**	10mm white reflective tile; 50mm screed concrete; 50mm Weathering course; 200mm RCC slab; 10mm Interior plaster, **U_{roof}= 1.82 W/m^2.K**	6mm Single clear glass, U_{glass}=5.7 W/m^2.K, SHGC=0.83	12.6%	0.67	**10.9**
Project 4	Longer sides are orienting towards NW-SE	Pune	15-storey	20mm Plaster (external); 150mm Fly Ash brick; 15mm Plaster (Internal), **U_{wall}=2.6 W/m^2.K**	15mm Plaster (External);150mm RCC;10mm Plaster, **U_{roof}= 3.3 W/m^2.K**	6mm Single clear glass, U_{glass}=5.8 W/m^2.K, SHGC=0.82	20%	0.62	**20.1**
Project 5	Square planform	Thane	18-storey	20mm Plaster (external); 200mm AAC blocks; 10mm Plaster (Internal), **U_{wall}=0.77 W/m^2.K**	Roof: 15mm Plaster (External);150mm RCC;10mm Plaster, **U_{roof}= 3.3 W/m^2.K**	6mm Single reflective glass, U_{glass}=5.7 W/m^2.K, SHGC=0.55	41.3%	0.40	**16.0**

	Project Details			Construction Details			Calculated		RETV
	Orientation	Location	No. of storeys	Walling details	Roofing details	Glass details	WWR (%)	$SHGC_{eq}$	Total W/m^2
Project 6	Longer sides are facing N-S orientation	Thane	15-storey	20mm Plaster (external); 200mm AAC; 10mm Plaster (Internal), **U_{wall}=0.77 W/m^2.K**	20mm Plaster (External); 50 mm thick XPS insulation; 200 mm thick concrete slab; 150 mm thick brickbat coba; 10mm Plaster, **U_{roof}= 0.12 W/m^2.K**	6mm Single reflective glass, U_{glass}=5.7 W/m^2.K, SHGC=0.55	16.1%	0.34	**7.0**
Project 7	Longer sides face E-W orientation	Mohali	Stilt+5 storey	20mm Plaster (external) 230 mm Brick wall; 40 mm air cavity; 115 mm brick wall **U_{wall}=1.2 W/m^2.K**	White reflective tile (external); 40mm PUF insulation; 150mm RCC slab; 12mm Plaster (Internal), **U_{roof}= 0.73 W/m^2.K**	6mm Single reflective glass, U_{glass}=5.7 W/m^2.K, SHGC=0.55	16.6%	0.38	**12.8**
Project 8	Longer sides face E-W orientation	Ghaziabad	26-storey	20mm Plaster (external); 200mm Monolithic concrete; 15mm Plaster (Internal), **U_{wall}=3.0 W/m^2.K**	40mm china mosaic tiles; 50 mm mud phuska; Brick Bat Coba; 150 mm RCC; 10 mm (interior plaster); Inside roof surface, **U_{roof}= 1.86 W/m^2.K**	6mm Single clear glass, U_{glass}=5.8 W/m^2.K, SHGC=0.83	20.1 %	0.56	**24.5**

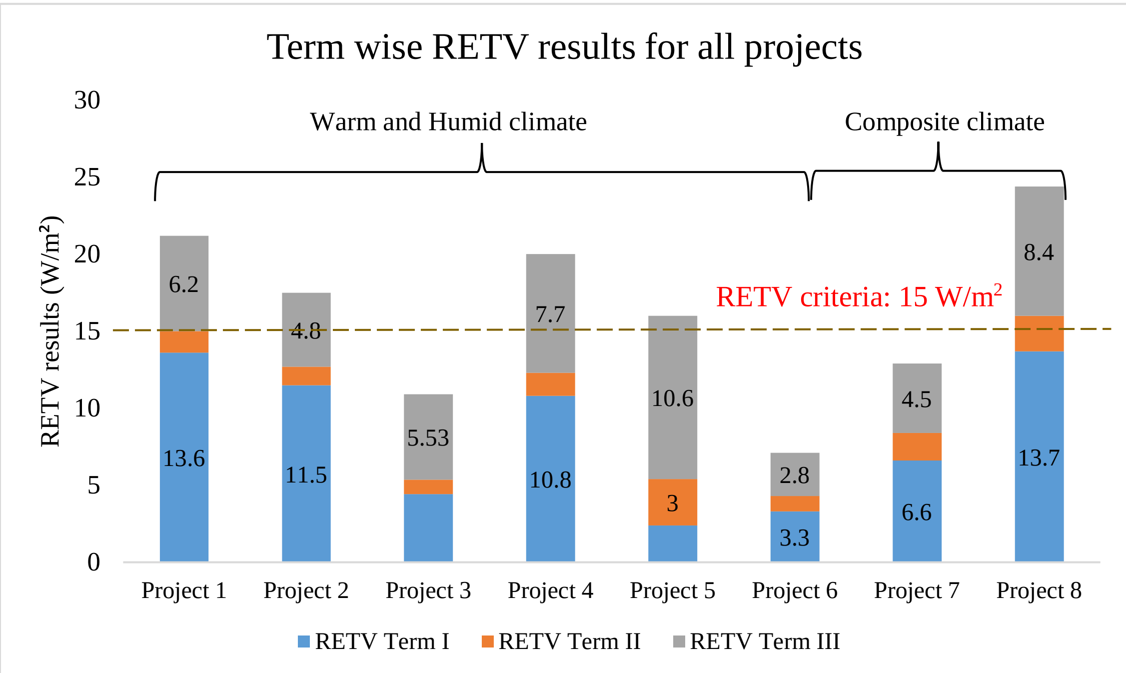

Figure 3: Term wise RETV results for all residential projects

* *The cost calculations are done as per CPWD DSR 2018. The rates are likely to vary significantly across the country.*

Figure 3 summarises term-wise RETV results for all eight residential projects. As mentioned before, RETV Term I is dependant on wall construction properties, Term II is dependant on thermal conductivity of the glazing used and Term III is dependant on external shading and SHGC of the glazing used.

Explanation of results are as follows-

Project 1: The RETV is 21.1 W/m^2. There is excess heat gained from wall conduction due to East-West facing orientation and walling made of monolithic concrete (large Term I) . Although, the residential block for

- Project 2: The RETV is 17.5 W/m^2. This residential sample presents an interesting case where inspite of having wall material as 200mm monolithic concrete, the overall RETV value is less as compared to Project 1, this is due to longer sides oriented towards N-S and use of single reflective glass.
- Project 3: The RETV is 10.9 W/m^2. It is relatively less due to use of industrial slag brick which has low thermal conductivity and has reduced the impact on wall conduction significantly. However, due to inadequate shading, the impact of window transmittance is still high.
- Project 4: The RETV is 20.1 W/m^2. The reduced thickness (150 mm) of fly brick wall results in higher U value of wall (2.6 W/m^2.K) as compared to a standard 230mm brick wall (2 W/m^2.K). Due to inadequate shading (only overhang) and choice of single clear glass (high SHGC), Term III is also high.
- Project 5: The RETV is 16 W/m^2. This sample presents an interesting case where inspite of using AAC blocks (U-Value: 0.77 W/m^2.K), single reflective glass and box-type shading as energy efficiency measures, it is not meeting RETV compliance requirements. This is due to high WWR~41.3% which is impacting Term II and Term III.
- Project 6: This project achieves lowest RETV of 7 W/m^2 which is much below the code compliance criteria of 15 W/m^2. Use of AAC blocks reduces the amount of heat gained due to wall conduction, thus Term I is less. There is no exposure to solar radiation from east and west facades through window openings, adequate shading has been provided for north and south facades. Single reflective glass which has lower SHGC (0.55) as compared to a single clear glass (0.83) has been used. This residential sample distinctly highlights that use of an efficient building envelope, including the roof assembly that meets the ECBC-R compliance criteria for roof (<1.2 W/m^2.K) can easily meet the RETV compliance requirements for the code.
- Project 7: The RETV is 12.8 W/m^2. Usage of brick cavity wall with 40mm air gap has reduced the heat gained due to wall conduction. Also, use of single reflective glass instead of single clear glass and adequate shading has also reduced heat gained due to window transmittance.
- Project 8: The RETV is 24.5 W/m^2 which is a high-rise apartment. There is excess heat gained from wall conduction due to East-West facing orientation and walling made of monolithic concrete. Openings facing east and west orientation have inadequate shading such as overhangs which are not able to fully shade the openings. Therefore, heat gained due to window conduction and window transmittance is also high.

CONCLUSION

While reading the conclusions of the study, it should be remembered that the study presents results of only limited number of building projects. These projects may not cover all types of construction and hence are not fully representative of the new residential construction taking place in the country. However, the analysis of the project data does provide useful information on building materials and building design features which can help in meeting the code compliance. While this study presents results of only eight building projects, if such an analysis is carried on for a large number of residential projects, it can also help in future code development and revision of the code.

The measures recommended below are for new construction as per the code.

a) The RETV of the building projects varies from a minimum of 7.0 W/m^2 (Project 6) to a maximum of 24.5 W/m^2 (Project 8). Three projects (project 3, 6 & 7) meet the RETV compliance (RETV ≤15 W/m^2)

b) Term I and Term III have the largest influence on RETV.

c) The Term I, depends primarily on the U_{wall}. Projects 1,2& 8 (monolithic concrete construction) and project 4 (150 mm fly ash brick wall) have high U_{wall} ($U_{wall} \geq 2.6$ W/m^2.K) and consequently have large Term I; all these four projects does not meet RETV compliance. Use of AAC block (Project 5&6), industrial slag brick (Project 3) and cavity wall (Project 7) results in low U_{wall} ($U_{wall} \leq 1.22$ W/m^2.K) and smaller term I. Three out of these four projects meet the RETV compliance. It can be concluded that the choice of walling material assembly is critical for RETV compliance.

d) The Term II is relatively small compared to Term I and III and has less influence on RETV. However, Project 5 has largest Term II (Term II = 3.0 W.m^2), primarily due to large WWR (WWR =41.3 %). This means that for projects with large WWR, use of double glazing can bring substantial reduction in RETV.

e) Term III which depends on WWR, shading and SHGC of glazing varies from a minimum of 2.8 W/m^2 (Project 6) to the maximum of 10.6 W/m^2 (Project 5). Projects having high WWR, higher glazed area oriented towards east and west, and having higher $SHGC_{equivalent}$ are observed to have large Term III. Project 6 has the minimum term III of 2.8 W/m^2.K, this project has a WWR of 16.1 % and low equivalent SHGC of 0.34.

f) For the ENS code provision of U-value of the roofing material, out of the eight projects, two projects i.e. Project 6 and 7 (Figure 4) are able to achieve a U_{roof} value of less than 1.2 W/m^2.K by use of insulation materials such as XPS (Extruded Polystyrene) and PUF (Polyutherane foam).

g) The typical cost of measures to reduce RETV and U_{roof} are given in

h) Table 2 provides typical cost of some measures to reduce RETV and U_{roof} as per CPWD DSR 2018 (Indo-Swiss BEEP, 2019)

Table 2: Typical cost of some of the measures to reduce RETV and Uroof as per CPWD DSR 2018 (Indo-Swiss BEEP, 2019)

	Measures	Cost
Wall (The cost of 230mm brick wall with finishing is ₹2400*/m^2).	230mm Brick cavity wall with 40 mm insulation	₹3000*/m^2
	200mm AAC blocks	₹2000*/m^2
	200mm Hollow clay blocks	₹2700*/m^2
Roof (The cost of 150 RCC roof with finishing is ₹ 1800*/m^2)	RCC slab with 50mm PUF insulation	₹3150*/m^2
	RCC slab with 100mm foam concrete insulation	₹2650*/m^2

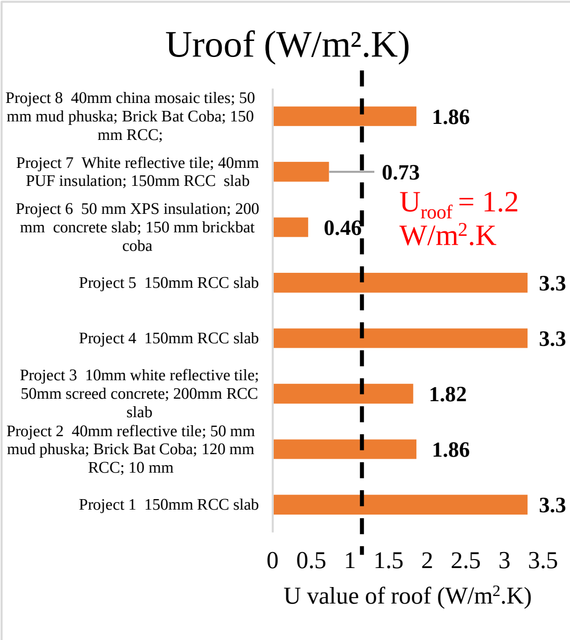

Figure 4: U-values of roofing material for all residential projects

ACKNOWLEDGEMENT

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APPENDIX

A.1 Project wise details

a) Project 1: Warm & Humid climate

This completed apartment project (2018) is located in Chennai comprising of 2,3 bedroom, hall and kitchen (BHK) units. The RETV evaluation is carried for 3-typical towers of 19-storey each. Each tower consists of 152 dwelling units with a carpet area ranging from 75-110 s m^2 per unit. Longer sides faces E-W orientation (Figure 5).

Shading: Box type shading provided, $SHGC_{equivalent}$=0.54

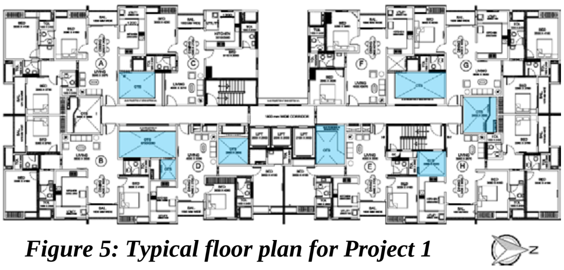

Figure 5: Typical floor plan for Project 1

b) **Project 2: Warm & Humid climate**

This completed (2016) apartment project is located in Chennai comprising of 2-BHK units. It is a 4-storey building comprising of 56 dwelling units. The carpet area ranges from 58-65 m^2 per unit. Longer sides face N-S orientation (Figure 6).

Shading: Most openings have left and right side fins, openings enclosed with balconies have box-type shading, $SHGC_{equivalent}$=0.46

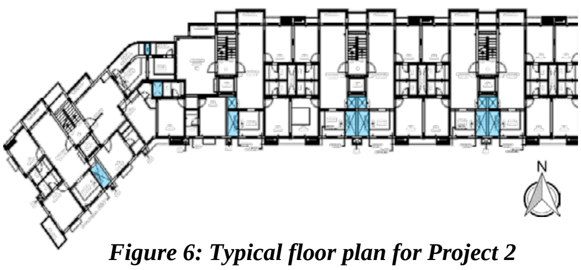

Figure 6: Typical floor plan for Project 2

c) **Project 3: Warm & Humid climate**

This is an indvidual low-rise housing project located in Chennai, its construction has been completed. It is a G+1 building with a carpet area of 257 m^2. Longer sides are orienting towards NW-SE (Figure 7).

Shading: No shading provided on NW orientation and some SE openings. Side-fin provided on other openings and overhang on balcony facing openings, $SHGC_{equivalent}$=0.67

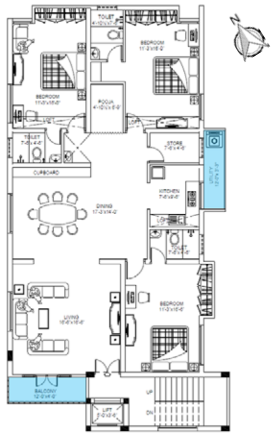

Figure 7:Second floor plan for Project 3 (G+1 storey)

d) Project 4: Warm & Humid climate

This is an EWS housing block of an apartment society in Pune, the project is at its design stage. The block is 15-storey comprising of 150, 1-BHK dwelling units with a carpet area of 40 m^2 per unit. Longer sides are orienting towards NW-SE (Figure 8).

- Shading: Maximum no. openings at North-West orientation with 0.6m overhang, building projection acting as a side-fin for some openings. No openings provided at South-East orientation. $SHGC_{equivalent}$=0.62

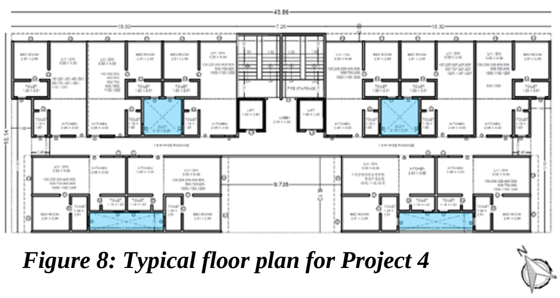

Figure 8: Typical floor plan for Project 4

e) Project 5: Warm & Humid climate

This project design is proposed under state government authority at Thane. It is a G+17 storey building with 42, 1-BHK dwelling units. The carpet area ranges from 23-51 m^2 per unit. It has a square planform (Figure 9).

- Shading: Balcony slabs and building projections acting as shading devices. $SHGC_{equivalent}$=0.40

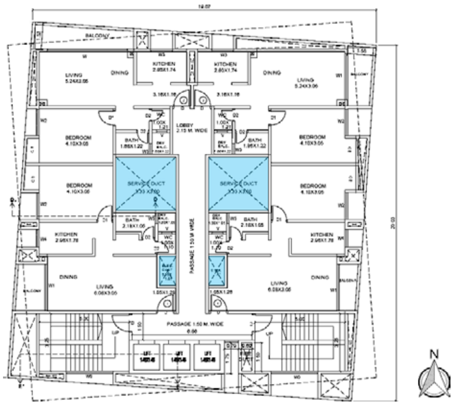

Figure 9:Typical floor plan for Project 5

f) Project 6: Warm & Humid climate

An under construction low cost housing project under state government authority at Thane, it comprises of 82, 1-RK units with a carpet area of 26.3 m^2 per unit.. It is a 17-storey building with 15 floors of residential units and remaining 2 floors of commercial shops. Longer sides are facing N-S orientation (Figure 10).

Shading: East and West facades do not have openings. In North and South facades, all openings have box-type shading (0.5m), $SHGC_{equivalent}$=0.34

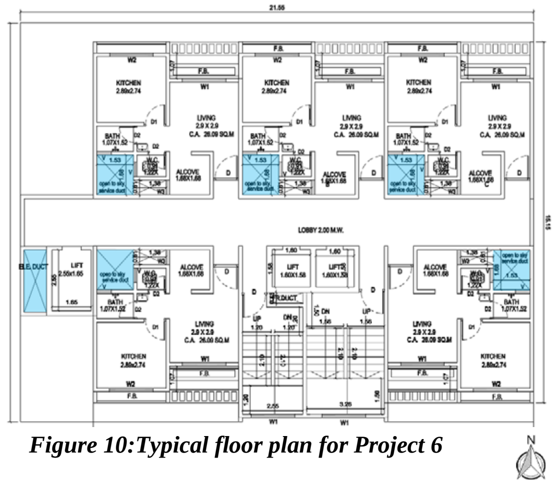

Figure 10:Typical floor plan for Project 6

g) Project 7: Composite climate

This project is a residential quarters (only block II) build for a development financial institution (DFI, India) at Mohali which is under construction. It is a Stilt+5 storey building with 20 dwelling units. The carpet area of these 2-BHK units range from 81-97 m^2 per unit. Longer sides face E-W orientation (Figure 11).

Shading: Balcony slabs and building projections acting as shading devices. More opening area towards east and west orientation. Most of the openings have box type shading on north and south face. $SHGC_{equivalent}$=0.38

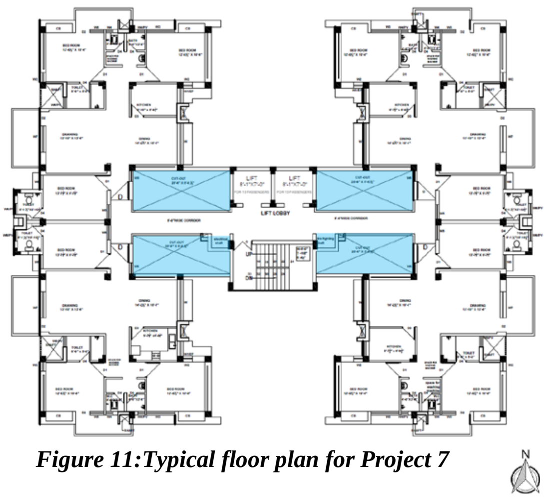

Figure 11:Typical floor plan for Project 7

* *The cost calculations are done as per CPWD DSR 2018. The rates are likely to vary significantly across the country.*

h) Project 8: Composite climate

An under-construction apartment housing project located in Ghaziabad. A 26-storey block comprising of 240 dwelling units. The carpet area of these 3-BHK units are 74 m^2 per unit. Longer sides face E-W orientation (Figure 12).

- Shading: Balcony slabs and building projections acting as shading devices. East and west facades consist of box-type shading, openings with maximum area at north and south facades have overhangs shading the balcony openings. $SHGC_{equivalent}$= 0.56

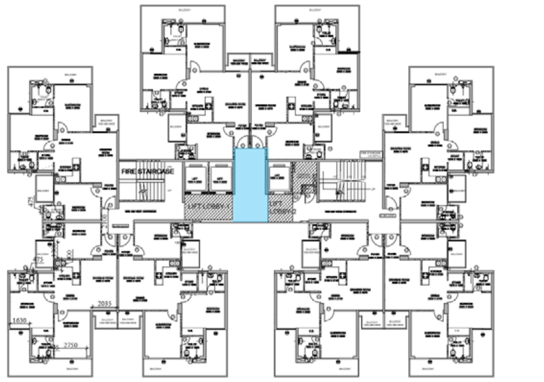

Figure 12:Typical floor plan for Project 8

CLIMATE CHANGE RESILIENCE OF PASSIVE ENERGY EFFICIENT SOLUTION PACKAGES RECOMMENDED BY BEEP FOR RESIDENTIAL BUILDINGS

Naga Venkata Sai Kumar Manapragada[1], Bibhu Kalyan Nayak[2]

[1]*Energy Analyst,*
Integrative Design Solutions Private Limited,
New Delhi, India
naga@ids-pl.com

[2]*Assistant Professor, School of Architecture and Design*
Manipal University Jaipur
Jaipur, India
bibhukalyan.nayak@jaipur.manipal.edu

ABSTRACT

Purpose: The residential survey conducted by Indo-Swiss Building Energy Efficiency Project (BEEP) inferred space cooling and fans as major contributor (33%-65%) in residential energy consumption. In this regards, passive energy efficient solution packages for building envelop were recommended by BEEP to reduce cooling thermal energy demand in living and bedroom. The present study intends to identify the potentiality of these strategies in reducing cooling energy consumption for future climate scenarios.

Approach: Through transient building energy simulations, the provided baseline model and energy efficient solution packages thermal performance would be evaluated for present-day, 2050 and 2080 climate scenarios. The typical weather files for 2050 and 2080 are predicted based on Hadley Centre Coupled Model, version 3 through Climate Change World Weather File Generator.

Findings: The savings through thermal comfort adaptation decrease rapidly along with increase in cooling degree-days and number of air-conditioners usage. The high-performance air-conditioning strategy could act as curing solution to reduce cooling energy consumption for residential buildings with poor envelope. The BEEP envelope packages could derive more cooling energy savings with increase in air-conditioners ownership. The study understands that external shading system could be key intervention to reduce cooling requirement for future climate change conditions. The control strategy for shading operation should be revised based on changing climatic conditions.

Value: By developing a storyline based on AEEE report, the study deduced that BEEP package-2 could provide better savings in climate change scenario over bussiness-as-usual envelope case even when energy conservation measures like IMAC-MM adaptation and COP-3.9 air-conditioning considered.

Keywords—*Climate change, Cooling Energy Consumption, Energy Performance Index, Cooling degree-days and Heating degree-days*

INTRODUCTION

The 2011 census revealed that the cities with more than 1 million population has increased from 35 in 2001 to 53 in 2011. The Government of India (GoI) in 2015 launched Pradhan Mantri Awas Yojana – Housing for All (PMAY) scheme to address the housing shortage issue in both Urban and Rural communities in India. Along with increasing residential footprint, it is expected to have additional electricity consumption in the domestic building sector. The ENERGY STATISTICS 2019 (MoSPI., 2019) reported domestic sector electricity consumption as 2,71,258.6 GWh. Compared to consumption observed in ENERGY STATISTICS 2018 (MoSPI., 2018), it is 6% higher. The increase in domestic electricity consumption in India is not only governed by the rising residential footprint. Increase in appliance ownership could be the undeniable factor for rise in residential energy consumption. Sahil Ali (Ali, S., 2018) predicted additional 438 to 623 TWh of energy consumption by 2030 due to residential appliances. He also detailed that the electricity consumption rise would be from comfort cooling systems, common services and electric cooking. The advancement in applied sciences and information technology providing solutions for energy efficiency across all sectors. The market disrupting energy efficient house-hold appliances may reduce the demand but cannot avoid rise in demand completely in residential sector. Alliance for an Energy Efficient Economy (AEEE) in one of its articles (AEEE, 2018) estimated that around 8% of Indian house-holds possess air-conditioners. The article also predicted the percentage of ownership may rise to 21% by 2027-28 and 40% by 2037-38.

Along with rise in air-conditioners ownership, Climate Change is expected to influence the cooling energy demand in future. India located in tropical zone usually possess extreme weather conditions. In summer season, the temperatures extend beyond 35°C and 40°C in Warm-Humid and Hot-Dry/Composite climates respectively. The study conducted by Dr. Guleria and Dr. Gupta (Guleria, S. and Gupta, A. K., 2018) revealed that Indian cities are vulnearble to heat wave conditions due to urban heat island effect. The study specified that air pollution, high density urban built forms and air-conditioners going to encourage the heat wave conditions in urban spaces. The authors hypothesize that in-future longer duration heat wave scenarios in India transform the ownership of air-conditioning into necessity for survival.

The climate change studies in building sector are being performed in multiple countries to assess the vulnerabilities. The study (Zhai, Z. J. and Helman, J. M., 2018) conducted in United States (US) for seven climatic zones inferred that rate of increase in cooling energy consumption will be higher than decreasing heating energy requirement. Victor Perez-Andreu and team in their study (Pérez-andreu, V. et al., 2018) predicted that the passive strategies related to natural and forced ventilation will have low or no impact in reducing the cooling demand. One of the studies identifying the savings in cooling energy consumption through adaptation was conducted in Spain (Sánchez-garcía, D. et al., 2019). The study observed savings upto 74% for cooling and 43% for heating by chosing adaptive thermal comfort setpoints with mixed mode operation. The study (Manapragada, N. V. S. K. et al., 2017) conducted in India for composite climate projected savings around 30% by retrofitting and adaptation. Similar studies were performed using various climatic models and climate change scenarios in different climates. The common interpretation observed in all the referred studies was increase in cooling energy consumption and decrease in heating energy requirement.

The multi-storey residential building typology gained popularity in the Indian building sector for its pontentiality to accomodate high occupant density in less site area. The Indo-Swiss Building Energy Efficiency Project (BEEP) performed survey in Chennai and New Delhi in 2009 to evaluate the energy performance of multi-storey residential buildings. The BEEP study infered that the average energy performance index (EPI) excluding common services was 48 kWh/m^2.year (BEE. 2014) and 44 kWh/m^2.year (BEE. 2016) for Warm-Humid and Hot-Dry/Composite climates respectively. In both studies space-cooling (air-conditioning) and fans were observed to be the major stakeholders in residential consumption. The study proposed design guidelines and recommendations related to building envelope, space cooling, indoor appliances and common services to prove energy efficiency in multi-storey residences. Specifically, the study projected savings in cooling thermal energy demand through passive energy – efficiency solution packages for the present-day climatic condition.

This research intends to understand climate change resilience of passive energy – efficiency solution packages proposed by BEEP in comparision with the thermal performance adaptation and efficient air-conditioner retrofitting. The aim of this reseach has been categorised into following objectives

- Evaluate the cooling Energy Performance Index (EPI) for bussiness-as-usual (BAU) and energy efficient strategy deployed cases in subjection to climate change
- Analyse the deviation in cooling EPI savings based on climate change conditions, adaptation levels and air-conditioning usage scenarios
- Determine the climate change resilient and climate change vulnerable strategies

METHODOLOGY

The present study finds transient building energy simulation approach resourceful in establishing the evaluation objective. EnergyPlus (EP), the open-source developed by US Department of Energy (DOE) has been employed by the study for the simulation task. EP requires representative weather file of the climate, building model and equipment load details along with usage pattern.

LOCATION

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Buildings & Communities
Energy Efficiency for Business Competitiveness
Urban Infrastructure & Utilities
Authors' Index

The BEEP proposed first two energy – efficiency solution packages for Warm-Humid, Hot-Dry and Composite climates in which common guideline has been launched for Composite and Hot-Dry climates. Therefore, the authors elected Chennai and Delhi locations that represent Warm-Humid and Composite climates respectively for the study.

PRESENT-DAY WEATHERFILES

The EP requires weather files encoded in EnergyPlus Weather (EPW) format. The present-day weather files availed (http://climate.onebuilding.org/) for the chosen locations are typical meteorological year (TMY) files. The TMY files are composed by concatenating each month chosen from different historical dataset. The each month selected represents the average climatic conditions of the historical dataset. The potentiality in TMY is that it doesnot inculcate the weather extrimities that appear rarely for the given location. In 2014, the weather files were updated for the Indian cities by The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), Malaviya National Institute of Technology (MNIT) and The International Institute of Information Technology Hyderabad (IIIT-H).

FUTURE WEATHERFILES

Similar to present-day weather files, future weather files representing climate change conditions for the given location is the key for this study. The rate of climate change intensity is dependent on intensity of anthropogenic emissions. The Intergovernmental Panel on Climate Change (IPCC) in its third assessment report (IPCC, 2001) classified the emission scenarios based on economical, social, technological, demographical and fuel usage advancement. The Atmosphere Ocean General Circulation Model (AOGCM) is the mathetical model referred for weather and climate change forecasting. The meteorological research institutes across the world have been developing General Circulation (GCMs) and Regional Circulation Model (RCMs) based on emission scenarios developed by IPCC report. These GCMs and RCMs aid the researcher to extract future weather data embedded with climate change effects for vulnerability assessment.

The climate change world weather file generator (CCWorldWeatherGen) developed by Sustainable Energy Research Group of University of Southampton enables the users to generate climate change weather files for cities across the world. The Excel based tools requires HadCM3 climate change scenario data and present-day weather file of the respective location to generate typical future weather files for 2020, 2050 and 2080 in EPW and TMY file formats.

REPRESENTATIVE BUILDING MODEL

The similar climate change impact studies referred in this article either performed bulk model simulation or representative model simulation for the analysis. In the bulk model simulation, the buildings in city-level or district-level are modelled and simulated at once. This method is computationally expensive to perform and resourceful for the studies comprising urban scale objectives such as investigating peak energy demand and district cooling energy demand. Representative model simulation method involves modelling and simulating the building that architecturally represents the target building typology of the region.

The model geometry referred in this study was one of the representative residential prototype inferred by BEEP post their survey and research on multi-storey residences in all over India. The 80 sq.m –Tower type residential building model shown in **Figure 1** assumed to have two bedrooms 16 sq.m each along with 40 sq.m living room and 8 sq.m kitchen in each unit. As the units were aligned accordingly to all four direction, the requirement to simulate by rotating the model for 90, 180 and 270 degrees for normalising orienatation effect was avoided. The three exposed facades in the model possess fenestrations with Window-to-Wall Ratio (WWR) of 15%.

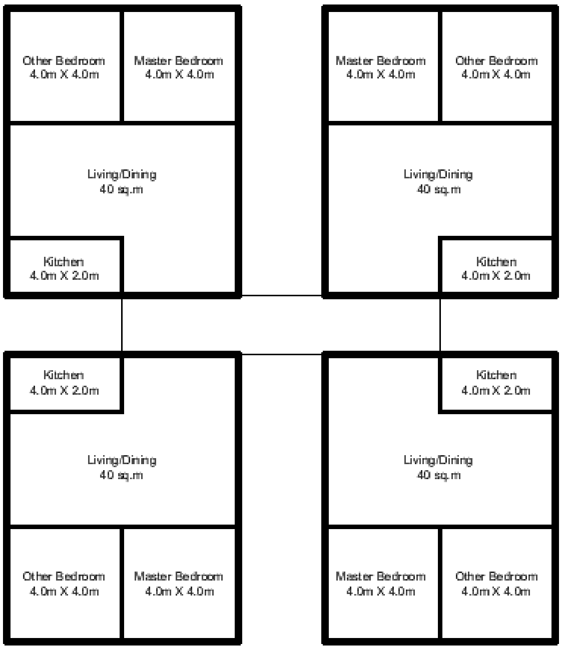

Figure 1 Layout of the representative model

MODEL INPUTS

As discussed in the paragraph-1 in Methodology section, the EP requires representative weather file of the climate, building model and equipment load details along with usage pattern for simulation. The research objectives ascertained comprise many IF-THEN conditions for the model inputs. For instance, the façade thermal properties varies for BAU case and passive energy – efficiency solution packages. Thus the present study segregates the model input options into conditions, cases, levels, scenarios and retrofit options.

Climatic conditions

The analysis should be performed for present-day and future climatic conditions. The typical weather files representing the present and future climate change conditions are grouped into 2014_epw, 2050_epw and 2080_epw for the two climatic zones chosen. The 2014_epw represent the present-day weather files for the given location. The 2050 and 2080 EPW files generated from CCWorldWeatherGen are termed as 2050_epw and 2080_epw for both climatic conditions.

Envelope input cases

The thermal properties of building vary for BAU and passive energy – efficiency solution packages (PEES). The BEEP guidelines proposed three PEES packages and the present study chosen the first two PEES packages that can be applied for Warm-Humid and Composite climatic zones selected. Additionally, the first two packages observed to be economical in comparision with third package. The first PEES package (PEES-1 case) and second PEES package (PEES-2 case) differ by providing external movable blinds with 10% transmission. **Table 1** shows the envelope inputs for the three cases referred from BEEP guidelines (BEE., 2014 & BEE., 2016).

Thermal comfort adaptation levels

The energy consumption of air-conditioner (Window or Split air conditioninsystems) not only rely on the operating time but also based on the operating temperature. The operating temperatures are decided based on the thermal adaptation rate of the occupants. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed commont adaptive comport model that can derive comfort setpoints for each month based on mean monthly temperatures. Later, the Centre for Environmental Planning and Technology (CEPT) University has developed Indian Model for Adaptive Comfort (IMAC) for Naturally Ventilated (IMAC-NV), Mixed Mode (IMAC-MM) and Mechanically Ventilated (IMAC-AC) buildings individually. Equations – (1), (2) and (3) referred from Energy Conservation Building Code 2017 (Bureau of Energy Efficiency, 2017). The present study chosen constant adaptation level with cooling setpoint of 24°C for Basecase. To account the cooling energy savings, the study generated IMAC-MM and IMAC-NV cooling setpoints for 2014_epw, 2050_epw and 2080_epw of Chennai and Delhi.

$$\textit{IMAC-NV: Indoor operative Temperature} = (0.54 \times \textit{Outdoor temperature}) + 12.83 \quad (1)$$

$$\textit{IMAC-MM: Indoor operative Temperature} = (0.28 \times \textit{Outdoor temperature}) + 17.87 \quad (2)$$

$$\textit{IMAC-NV: Indoor operative Temperature} = (0.078 \times \textit{Outdoor temperature}) + 23.25 \quad (3)$$

Table 1: Envelope inputs for three cases

ENVELOPE INPUT	BAU	PEES-1	PEES-2
External Wall U-Value [W/m^2.K]	2.0	0.7	0.7
External Wall Surface Solar Reflectance	0.3	0.7	0.7
Glazing U-Value [W/m^2.K]	6.1	6.1	6.1
Glazing SHGC	0.85	0.85	0.85
Glazing VLT	0.9	0.9	0.9
Local Shading depth	500mm	500mm	500mm
Local Shading elongation either sides	0mm	500mm	500mm
Window-to-Wall ratio	15%	15%	15%
Window external blind shading	-	-	Yes

Cooling energy consumption scenarios and retrofit options

The number of air-conditioners ownership per residential unit is not constant especially in India. The AEEE (AEEE, 2018) projected rise in air-conditioners per house-hold by 1.5 and 2 for 2027-28 and 2037-38 respectively. To evaluate savings scenarios across households with multiple air-conditioners, the present-study Low Energy Profile Consumption (LEPC), Average Energy Profile Consumption (AEPC), and High Energy Profile Consumption (HEPC) scenarios. In the case of LEPC scenario, only Master bedroom is conditioned and for AEPC scenario both Master bedroom and Other bedroom are conditioned. All the rooms except Kitchen are conditioned for HEPC scenario.

The electricity/energy consuming appliances are categorised into constant loads and variable loads. The appliances such as air-conditioners which not only rely on operational time and influence by climatic variables are termed as variable loads. In this study, constant loads with same wattage and usage pattern are modelled. The usage pattern for both constant and variable loads has been referred from study (Garg, V. et al., 2013) conducted by IIIT-H for WinBuild Inc. The one retrofit option for air-conditioning has been introduced in the study to assess its performane in climate change situation. The Coefficient of Performance (COP) for air-conditioning systems in BAU has been assumed to be 2.7 (COP-2.7). In the retrofit option, the COP is assumed to be 3.9 (COP-3.9). Appliance like Geyser which is a variable load has been not modelled as the substantial studies could not been identified for Indian climatic zones to define operating setpoints. Ceiling fans also relate to variable load and the study (BABICH, F. et al., 2017) conducted by Loughborough University along with CEPT University shown impact of Ceiling fans in reducing cooling energy consumption. However, the study did not consider to model the ceiling fans and its influence on cooling load as the research is being conducted in depth at IIIT-H on the same research gap.

RESULTS ANALYSIS AND OBSERVATIONS

In this section, the climate change conditions predicted in weather files 2014_epw, 2050_epw and 2080_epw for both Chennai and Delhi will be discussed as first sub-section. The impact analysis will be discussed in the succeeding sub-section for considered cases, levels, scenarios and retrofit options.

CLIMATE CHANGE CONDITIONS

According ASHRAE 90.1-2004, the cooling degree-days (CDD@10°C) and heating degree-days (HDD@18°C) have been evaluated for present-day and future representative weather conditions. The analysis in **Figure 2** projected increase in CDD@10°C by 11.4% and 20% for 2050_epw and 2080_epw over 2014_epw in Chennai. Similarly in the case of Delhi, the rise was 15.8% and 27.9%. The Chennai didn't account any HDD18.3°C where as decrement has been observed for Delhi in 2050_epw and 2080_epw by 62.1% and 82.9% incomparision with 2014_epw. The outdoor hot-humid conditions [DBT>26°C & RH>60%] expected to increase for both Chennai and Delhi climates by 2050_epw and 2080_epw as shown in **Figure 3**. The increase rate of hot-humid condition has been noted to be higher in the case of Chennai compared to Delhi.

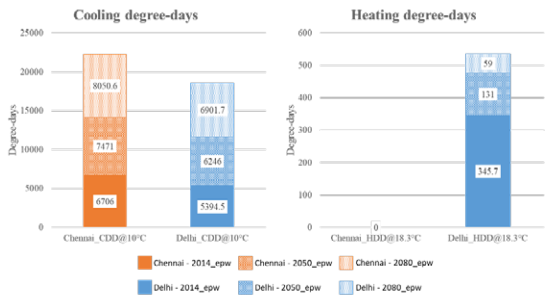

Figure 2 Cooling and Heating degree-days

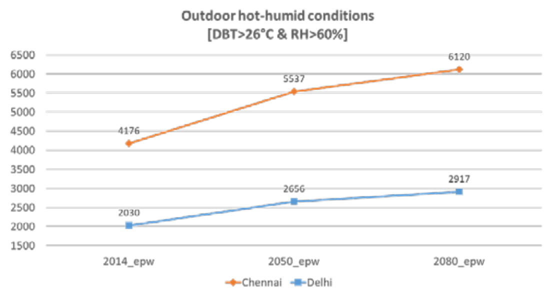

Figure 3 Outdoor hot-humid conditions

BASECASE COOLING EPI

The model with BAU envelope, constant cooling setpoint (24°C) and air-coditioner with 2.7 COP is referred as Basecase model for this study. The cooling EPI of Basecase model is evaluated for all energy consumption scenarios and climatic conditions. **Figure 4** explains the present-day cooling EPI for LEPC, APEC and HEPC scenarios along with increment observed for 2050_epw and 2080_epw future climatic conditions.

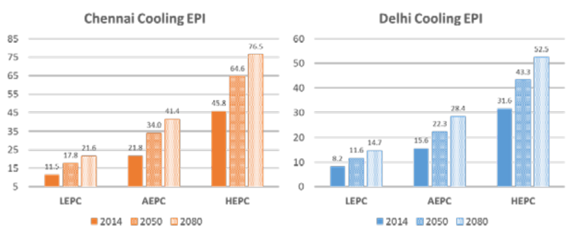

Figure 4 Basecase cooling EPI

Observation-1:

The cooling EPI increase rate for future climate observed to be similar for LEPC and AEPC in both climates. However, the HEPC cooling EPI increase rate for future climate was lower. The study hypothesizes that low solar exposure of living space facades due to mutual shading might have reduced the cooling load. Thus, total cooling EPI in HEPC case

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couldn't increase for future climate with the same rate observed in LEPC and AEPC scenarios.

Observation-2:

The analysis projected higher cooling EPI and rate of increase in cooling EPI for Chennai compared to Delhi. The study understands that higher cooling degree-days and increasing Hot-Humid conditions projected in 2050_epw and 2080_epw might be the reason for higher cooling EPI.

SAVINGS BY ADAPTATION

The constant cooling setpoint in Basecase model has been replaced with IMAC-MM and IMAC-NV adaptation scenarios to evaluate cooling EPI savings with adaptation. **Figure 5** details the savings achieved by IMAC-MM and IMAC-NV adaptation for multiple energy consumption scenarios and future climatic conditions in-comparision with respective Basecase energy consumption scenarios and future climatic conditions.

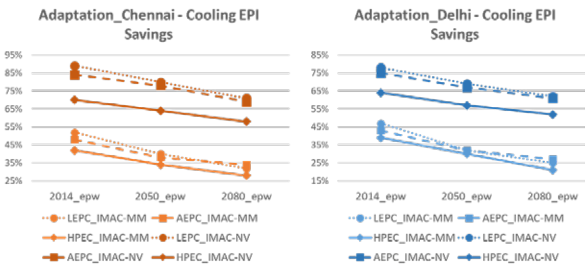

Figure 5 Cooling energy savings by thermal comfort adaptation

Observation-3:

For all energy profile scenarios and at different thermal adaptation conditions, the savings are expected to deplete at various rates due to climate change conditions. This observation infers that the rate of climate change is faster than the adaptation rate provided in the IMAC.

Observation-4:

The large variation can be observed in the case of HPEC IMAC-NV adaption condition for Chennai and Delhi Climate. Compared to LEPC, APEC has twice and HPEC four times additionally conditioned space which may the reason for large reduction in savings for IMAC-NV model.

Observation-5:

The rate of decrement in savings between 2014_epw and 2050_epw is higher than 2050_epw and 2080_epw for both climates and all adaptation conditions. The cooling degree-days between 2014_epw and 2050_epw is observed to be higher than increase between 2050_epw and 2080_epw. Thus, this study recognises the degree-days difference to be the cause.

SAVINGS BY COP

The Basecase model air-conditioning of COP-2.7 is replaced with retrofit option of COP-3.9 to understand cooling EPI savings achievable for all energy consuming scenarios and for present and future conditions. **Figure 6** shows 31% and 44% constant savings by COP-3.9 over COP-2.7 in Chennai and Delhi climates respectively under all climate change conditions and energy consumption profile scenarios.

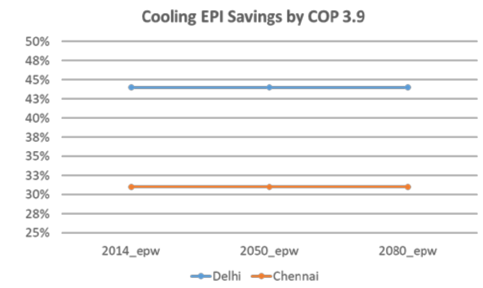

Figure 6 Cooling EPI savings by COP-3.9

Observation-6:

The constant savings registered for all future climate change conditions and energy consumption scenarios might be due to the reason of assuming same partload efficiency for both COP options. However, if cooling EPI between 2014_epw, 2050_epw and 2080_epw, there reduction in cooling energy savings can be observed.

Observation-7:

The analysis shows lower savings in the case of Chennai climate compared to Delhi climate. The study presumes higher latent load conditions might be the reason for loss in savings in Chennai climate.

SAVINGS BY PEES

The BAU case envelope has been replaced with PEES-1 and PEES-2 cases to assess the cooling EPI savings opportunity by BEEP recommended envelope for all energy consumption scenarios and present and future climatic conditions.

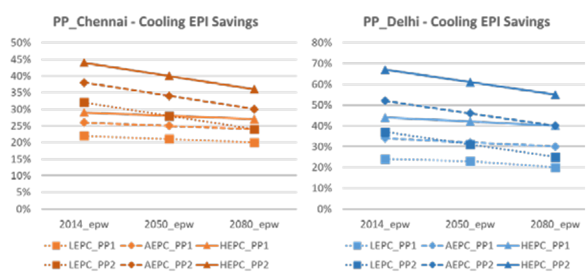

Figure 7 Cooling EPI savings by PEES

Observation-8:

The analysis in **Figure 7** shows that the Delhi climate expected to achieve greater savings from both PEES cases compared to Chennai Climate. The study understands that the Delhi climate viz., Composite is expected to achieve higher savings by utilising the low wall thermal conductivity, wall thermal mass, high reflective surfaces, and extended overhangs benefits from PEES-1 . Further additional savings from PEES-2 envelope strategies. However, Chennai being warm-humid climate may not avail the thermal mass benefit due to low diurnal variation condition. This might be the reason for larger savings in Delhi climate compared to Chennai.

Observation-9:

The cooling EPI savings for HEPC scenario is higher than AEPC and consequently LEPC scenario. The study presumes that the PEES strategies aided the air-conditioner by reducing its load over the time compared to Basecase envelope.

Observation-10:

Similar to adaptation strategies the study observed savings declination by 2050_epw and 2080_epw in both climates. Especially in Delhi, the bandwidth between energy consumers scenarios is higher. The believes that the increasing ambient temperatures in 2050_epw and 2080_epw may be the cause for reduction in savings.

Observation-11:

More than in PEES-1, the larger declination of cooling EPI savings is observed in PEES-2 for both the climates. **Figure 8** showcased the increase in sun hours with Direct Normal Radiation (DNR) less than 140Wh/sq.m which could be the faster rate of declination in cooling EPI savings in future climates.

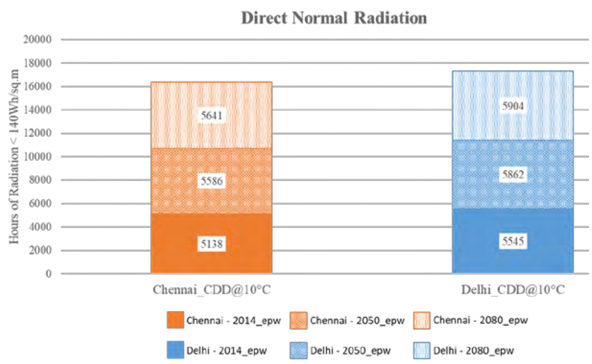

Figure 8 Hours with DNR less than 140 kWh/m^2

Observation-12:

Although cooling energy savings through PEES packages is less compared to thermal comfort adaptation levels, the depreciation rate of savings with respect to climate change condition is very less.

CONCLUSION

The following inferences are drawn based on the above discussed observations -

- The cooling energy savings through thermal comfort adaptation decrease rapidly along with increase in cooling degree-days and number of air-conditioners usage
- The high performance air-conditioners retrofitting strategy could act as curing solution to reduce cooling energy consumption for residential buildings with poor envelope
- The BEEP envelope packages could derive more cooling energy savings along with increase in air-conditioners ownership.
- The study understands that external shading system could be key intervention to reduce cooling requirement for future climate change conditions.
- The control strategy for shading operation should be revised based on changing climatic conditions.

To demonstrate the importance of PEES packages in predicted climate change conditions and increasing air-conditioner ownership scenario, the following storyline based evaluation methods has been adapted in this study.

The AEEE projected that around 0.80 billion m^2 of HIG, 5.37 billion m^2 of MIG, 4.72 billion m^2 of LIG and 2.21 billion m^2 of EWS residential footprint needs to be built post 2017-2018. Additionally, the air-conditioning ownership per residence is expected to increase. Therefore, the cooling energy consumption for future has been projected for the assumptions -

Assumptions

- By 2050, around 40% and 40% of the building stock is constructed in Warm-Humid and Composite/Hot-Dry climatic zones respectively
- HIG and MIG cooling EPI is equal to HEPC cooling EPI by 2050
- LIG and MIG cooling EPI is equal to AEPC cooling EPI by 2050

Path-1:

If the complete built-stock is designed with Basecase criteria, the residential cooling energy consumption expected to be 127.6 TWh by 2050 after considering IMAC-MM adaptation and COP-3.9 option.

Path-2:

If the complete built-stock is designed with PEES-2 criteria, the residential cooling energy consumption expected to be 95.0 TWh by 2050 after considering COP-3.9 option only.

In this storyline section, the study deduced that PEES-2 package could provide better savings in climate change scenario over BAU envelope even with IMAC-MM adaptation achieved.

ACKNOWLEDGEMENT

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A COMPREHENSIVE OVERVIEW OF DST'S CLEAN ENERGY RESEARCH INITIATIVE

Dr. Sanjay Bajpai[1], Dr. J B V Reddy[1], V Maharshi[2], Manoj Kumar S[3], Sai Kiran[4]

[1] *Department of Science and Technology, India*
sbajpai@nic.in
jbvreddy@nic.in

[2] *Indo-US Science & Technology Forum New Delhi, India*
maharshi.vadapalli@gmail.com

[3] *Mission Innovation IC 7 Resource Unit, DST, India*
arc.manojkumar@gmail.com

[4] *Indian Institute of Technology Delhi, India*
narik.sai8@gmail.com

ABSTRACT

India has committed to reduce the carbon intensity by 33-35% by 2030 as compared to its 2005 levels under the Paris agreement. The India Cooling Action Plan estimates that the commercial built up area is poised to grow at 2x within the next decade. This provides a unique window of opportunity for sustainable building stock. Promoting Building energy efficiency could be an intertwining solution to meet these commitments. Realising this need to curtail the emissions from the built environment, Department of Science and Technology (DST), The Government of India has embarked on several initiatives and flagship programs to drive habitat energy efficiency by supporting interdisciplinary, novel and transformative research. Through these flagship programs DST is catalysing interdisciplinary and collaborative research in the field of habitat energy efficiency. DST is playing an active role in the Mission Innovation program and has opened avenues for collaborative research in clean energy with 25 countries. This paper presents the structure of the above programs and discusses the thrust areas of research outcomes so far and their potential impact on energy efficiency. Key takeaways for policy formulation are discussed.

Keywords: Habitat Energy Efficiency, Clean Energy Research, International research program, National research program, Department of Science and Technology

INTRODUCTION

Green-House-Gas emissions are one of the century's biggest problems (Pachauri, R. 2007). India is the world's third largest emitter of greenhouse gases (GHGs), after China and the US. (Gütschow, J. et al 2016). Carbon emissions represent about 70% of complete GHG emissions (Global status report 2017). India has pledged a 33-35% reduction in the "emissions intensity" of its economy by 2030, compared to 2005 levels(INDC-UNFCCC, 2019).

The building industry accounts for 36% of worldwide energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions when upstream electricity generation is included. In the International Energy Outlook 2016 (IEO, 2016) reference case, delivered energy consumption in buildings worldwide increases by an average of 1.5%/year from 2012 to 2040. The building sector annual emission was around 3.7 Gt CO_2 in 2016. (Park et. al., 2018). The buildings' life cycle includes design and manufacturing of materials, construction, operation, and maintenance. The building material manufacturing and building operations are the 2 major life cycle carbon emission contributors (Wu.P, et al. 2019). The extraction and production accounts for 58% and operations account for 40% of the emission. The main proportion of energy-related CO_2 emissions in the construction industry are the indirect emission (e.g., energy generation emissions for electricity consumption and business heat) representing roughly 70 percent of the total buildings' operations related to energy emissions in 2017. Improving residential cooling equipment performance would save 3.5 EJ of energy to 2025 – slightly less than the total electricity use in India in 2015 (Global status report, 2017). A major challenge for reducing GHGs is the decrease in embodied carbon emissions within the building sector.

The emissions can be controlled by improving the efficiency, building system and control, development of low carbon thermally performing materials, envelope optimisation, better emission factors, and improved energy structure. Several research works are being done in carbon reduction at production and operations levels (Oh, B. K et al 2018), (Jung. H et al. 2019), (Mehdi Robati, D. et al 2019). Reddy proved that there is a 48% reduction of embodied energy of building systems through the use of alternative low carbon technologies (Reddy, 2009). It is critical to develop technological interventions to effectively manage the depleting energy resources. Buildings need to be designed and operated in response to the climate and occupant comfort needs. Given the market penetration of heating and cooling systems and the affordability of masses, there is a steady increase in energy demand for comfort conditioning in buildings. While in operation, such building systems and control need to be integrated for effective demand side control. In the Indian context there is also a strong need to develop open data bases of building performance to enable detailed research investigation on energy efficiency. To understand the efficiency and make a decision on alternatives, such reliable data is essential. In this context, DST is facilitating research and development in energy effiency and low carbon built environment to address such key issues in India.

The objectives of this paper are to (a) present a overview of global research programs in the field of clean energy and (b) present the structure of DST's funding in the field of energy efficiency and tangible outcome.

GLOBAL RESEARCH PROGRAMS

International funding agencies like the National Science Foundation-USA, Engineering and Physical Sciences Research Council-UK, European Research Council and Australian Research Council are facilitating research in clean energy habitat. Figure 1 shows the funding allocation for building energy research by the agencies in the past decade. The research themes fall in areas of building material, envelope system, life cycle assessment, Heating, ventilation, and air conditioning (HVAC) system improvement, monitoring and control of operations. The key areas include predictive control in building energy management through big data analysis, automatic building thermo regulations, smart micro grid-enabled buildings, fundamental envelope research, building occupant dynamics, phase change materials in concrete, advanced heating and cooling systems like geothermal, elastocaloric and displacement ventilation. The global trend in research in habitat and funding allocation shows the importance of clean energy research for a sustainable future.

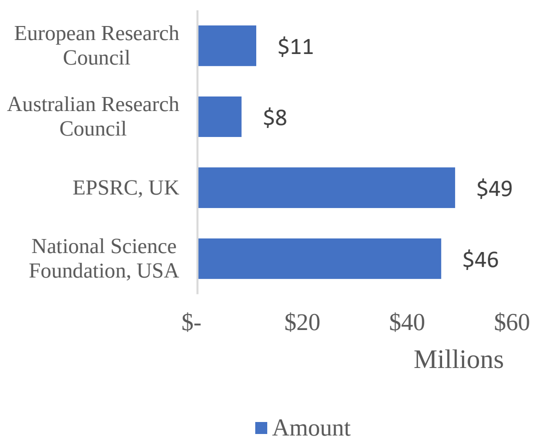

Fig 1: Global funding from major agencies in Building Energy Efficiency

DST'S CLEAN ENERGY MISSION

Department of Science and Technology, Government of India, under 'Clean Energy Research Initiative (CERI)' initiated an array of programs to support Research and Development in the area of Habitat Energy Efficiency. The programs are focused on promoting R&D activities to improve the energy performance of buildings and settlements. The programs are geared to support the enhancement of knowledge and practice to save energy in design, construction and operation of habitats.

Theese programs envisage support to India specific outcome based research in the areas of energy efficient building envelope technologies, low energy cooling systems, daylighting and electric lighting, building automation and controls for energy savings and research which can provide scientific inputs to policy formulation and help devise procedures, codes and standards. Thrust is to sponsor research towards scientific, engineering, design and technological solutions to overcome barriers to achieving energy efficiency. The projects under this program focus on translation research, converting existing knowledge or theory into design, processes or products. DST's priority is to support interdisciplinary research which is novel, transformative and eventually scalable and affordable.

It has researchers from over 10 engineering disciplines and over 5 applied sciences disciplines from over 30 organizations in India and abroad. Through these programs the research teams have been able to engage several industry stakeholders and agencies who are active in the field of building energy efficiency. This has enabled a platform for creating deployment ready technologies leading to energy demand reduction. The program has dovetailed well with international missions on energy demand reduction including Mission Innovation for accelerating clean energy revolution.

National Programs

National programs are intended to develop facilitate formation of national research networks, development of state of the art testing laboratories, development of new products in the form of materials, systems and tools for direct application in the field to enhance the energy efficiency.

DST created - Initiative to Promote Habitat Energy Efficiency (I-PHEE) program with an investment of 4.87 million USD

Thematic area	Number of Projects
Innovative Building Materials	12
ICT and Building Controls	10
Low Energy Heating and Cooling	5
Design Integration	7

Table 1: Thematic areas and Projects under IPHEE

DST has facilitated
- the development and full scale demonstration of technologies leading to the building energy efficiency.
- a wide range of application research and product development
- fundamental research contributing to the body of knowledge

Some of the significant endeavours include DC based building appliances such as air-conditioners, lights, fans and refrigerators, energy generating window panels, radiant cooling systems, smart shading devices and intelligent decision support system.

On the material sciences, the outcomes include high strength geo-polymer using fly-ash, products such as eco-friendly building materials manufactured from waste materials and low-cost biomass, self-cooling modular units, green wall panels and Phase Change Material integrated building materials, low density bricks from construction and demolition wastes, cellulose aerogel-fly ash nanocomposite, chromogenic material window system with onsite electricity generation potential and Micro/Nano encapsulated and eutectic Phase Change Material for window blinds.

International Programs

DST has supported Indo-US and Indo – UK programs which have a wide spectrum of deliverables and varied outcomes towards creating energy efficient built environments. The Indo-US program created a Joint Clean Energy Research and Development Centre to facilitate research and development on clean energy with an investment of 8.5 million USD. The projects awarded under the program are,

1. U.S.-India Joint Centre for Building Energy Research and Development (CBERD)
2. Improving Building Energy Efficiency (IBEE).

It enabled the research fraternity deploy clean energy technologies rapidly with greatest impact. INDO-UK projects target energy demand reduction in the built environment with an investment of 8.9 million USD. The projects awarded under the program are,

1. Residential Building Energy Demand Reduction in India (RESIDE)
2. Integrated Urban Model for Built Environment Energy Research (iNUMBER)
3. Zero Peak Energy Building Energy Design for India (ZED-i)
4. Community-scale Energy Demand Reduction in India (CEDRI).

INDO-UK projects have thrust areas of peak demand reduction, city and community level energy efficient technologies, integration of information, communication and renewable energy technologies bringing together joint solutions. This saw a wide network of Indian and UK research teams and industry stakeholders actively participating in research on energy demand reduction.

Tangible outcomes from DST's initiatives

The outcomes can be broadly categorised based on 4 major themes.

1.Innovative building materials

The major outcomes include development of encapsulated Phase Change Materials, standardized of low energy building components in compliance to ECBC / NBC 2016, glazing systems which enhances daylight penetration in buildings and development of phase change material incorporated building materials and components. Some of the teams are set to build full scale prototypes to demonstrate energy efficient strategies and innovative building materials.

2.Information & Communication Technology (ICT) and building controls

In this category, the projects deliver demonstrable technologies and full scale prototypes such as smart home energy management system, optimized geo-thermal heating and cooling system, tuned phase change material for peak demand reduction, building level peak demand suppression system, grid level peak demand optimization system, DC based lighting & control systems, prediction model of occupant behaviour under thermal stress, model for optimizing community energy profiles, prediction of community level energy demand profiles and demonstration of demand aggregation in the Indian residential sector. These will provide new tools and a firm evidence base to make better-informed decisions about the effects of future urban forms on energy use.

The projects formulate policy regulations for energy demand reduction. This includes energy efficiency implementation roadmap for residential buildings, customized solutions for demand reduction in 5 climate zones, community energy planning tool kit, deployment of ICT at the city level and providing inputs for major urban reforms, planning norms, building code enforcement, building code revisions and development of demand response policies, which would facilitate the settlement level energy management.

3.Low energy heating and cooling

Tangible outcome in this segment include modular Thermally Activated Solar Cooling and Ventilation Systems and Renewable Technologies such as Structure Cooling and Structure Heating. Research facilities for HVAC related research commissioned under this program include fault detection and diagnostic laboratory for testing the performance of the HVAC system, laboratory test facilities for alternate cooling systems and living laboratory for testing and validation of low energy heating and cooling systems. In addition, the development of low powered wireless occupancy sensor for energy savings in offices and classrooms, Integrated workstation control hub for integrating HVAC, lighting and plug load into one platform and predictive control tool for radiant slab cooling are some of the key outcomes. Apart from such facilities and products the program has yielded outcomes such as design criteria for non-conventional methods of heating and cooling systems and methodology of their implementation in buildings by design integration or as a retrofit for increasing efficiency of buildings.

4.Design integration – Roadmap for building energy efficiency

In this category, projects strive to strengthen existing body of knowledge and database, demonstrate full scale prototypes of technologies and policies for energy demand reduction. This includes creating repositories on metadata of energy use profile and thermal comfort for residential buildings across India, local weather files for building simulation for current and future climate scenarios, a new robust Occupant Response Model embedded within Energy plus for testing occupant response under peak load and development of building stock and municipal service energy model to help plan a secure energy supply for urban populations to be thermally comfortable and healthy. Other developments include daylighting lab developed as a part of simulating diffused and clear sky conditions and facilitate effective daylight integration, Thermal comfort chamber developed for testing the occupant comfort and artificial lighting test laboratory for testing of different light fixtures. With fundamental research, the existing knowledge set is strengthened by revising the Climatic Handbook and climate zones of India, developing Low Energy Design and Application Guide.

Project	Outcome
Innovative Building Materials	5% to 10% energy savings. 8 to 12% energy savings with PCM.
ICT and Building Controls	data-driven intelligent urban model
Low Energy Heating and Cooling	20% to 50% saving of energy drawn from the grid
Design Integration	An energy savings between 7% to 28%. 33% demand reduction

Table 2: Broad theme based project allocation and quantitative outcomes

Category	Infrastructure/Prototype	Location
Innovative Building Materials	Guarded hot box facility	Kolkata
	Accelerated aging lab for roof materials	Ahmedabad
	The PCM based TES integrated air-conditioned test room	Pondicherry
ICT and Building Controls	Double pane semi-transparent solar PV	Jaipur
	Grid simulator	Roorkee
	Simpod-Indoor environmental simulator	Roorkee
Low Energy Heating and Cooling	Solar & Biomass Cooling system	Rupnagar
	Solar Evaporative cooling system- Prototype	Mangalore
	Ground Source Heat Pump prototype	Roorkee
	Radiant cooling laboratory	Jaipur
	HFO refrigerant manufacturing set up	Hyderabad
	Low energy cooling test bed to study energy consumption and demand	Ahmedabad
	Thermal comfort chamber	Ahmedabad
	Test Workbench for control of Luminaire and window blinds	Manipal
Design Integration	Solar cold storage - Prototype	Tiruchirappalli
	DC convertor to drive home appliances directly from Photovoltaic - Prototype	New Delhi
	Light test laboratory	Hyderabad

Table 3: Few Infrastructure and prototypes developed by DST initiatives

In national programs, the products and technologies being developed has a potential for 20% to 30% energy efficiency. In addition, by effectively employing renewable sources the energy drawn from the grid can be reduced by about 40% to 50% depending on the type of appliances and the energy demand of the buildings. This will significantly vary between residential and non-residential buildings. Considering the building material, envelope products about 10% energy efficiency can be expected as a minimum baseline. Apart from this, alternate materials, heating and cooling systems will significantly contribute to minimizing environmental impact. In international programs, Indo-US projects promise energy savings between 7% to 28%. Indo-UK projects promise 30 – 40% energy savings and improved energy management. They will create energy benchmarks for residential buildings and develop a smart home energy management system.

data-driven intelligent urban model, technologies to achieve zero-peak energy demand with ⅓ energy demand reduction and demand side energy management at the grid and regional scale. Some of the prototypes already developed are shown in tables 2 and 3.

MISSION INNOVATION PROGRAM

Mission Innovation is a global initiative working to accelerate clean energy innovation. It endorses eight innovation challenges (ICs). India is a co-lead country in Innovation Challenge on Smart Grids. The smart grid innovation challenge aims over the next decade to develop and demonstrate the use of smart grid technologies and storage in a variety of grid applications, including demonstrating the robust, reliable operation of MW-sized micro grids in diverse geographic conditions. By 2030, the objective is to develop technology solutions that can accommodate 100% renewable based power plants in large scale across the globe.

As co-led of Innovation Challenge 1, DST published India Country Report on “Research, Development, Demonstration and Deployment of Smart Grids in India” and also published Smart Grids Innovation Challenge Country Report 2017 on Strategies, Trends and Exertions of Participating Countries (STEP) of 14 MI countries. DST supported 9 Projects with an investment of 10 million USD. 9 MI member countries - Australia, Canada, China, France, Germany, Italy, Norway, United Kingdom and United States of America are involved in the implementation of these projects. DST in collaboration with the Engineering and Physical Sciences Research Council (EPSRC) has identified Smart Energy Grids and Energy Storage as areas of significance in providing solutions of meeting future energy needs. 5 research proposals have been supported with an investment of 6.4 million USD focusing in the areas namely, Appropriate distributed storage technologies, On/off grid energy systems, DC networks and Control & communications, which are currently under joint implementations. India and UK together have set up virtual Joint Clean Energy Centre on Clean Energy. This centre focuses on integration of intermittent clean energy with storage for stable power supply at grid as well grid isolated communities. Two centres have been supported with the investment of 6.4 million USD.

India is a participant country in Innovation Challenge 7 (IC 7) which deals with Affordable Heating and Cooling of Buildings. IC 7 focuses on innovation through the use of new materials, processes, and systems provide a significant opportunity to reduce energy consumption and CO_2 emissions. Such innovative technologies and practices have important economic and social potential with respect to reducing energy bills, enhancing global access to energy, increasing the competitiveness of renewable technologies and improving energy security. IC7 has six priority areas- Thermal energy storage, Heat Pumps, Non-atmospheric heat sinks and sources, Predictive maintenance and optimization, Physiological studies for thermal comfort and Building-level integration. India is leading the thermal comfort priority area. This priority area is consisting of Thermal Physiology, Systems and Technologies and Operational controls.

GLOBAL COOLING PRIZE

DST in collaboration with Rocky Mountain Institute launched an innovation competition to develop a climate-friendly residential cooling solution that can provide access to cooling to people around the world without warming the planet. This ground-breaking competition is designed to incentivize development of a residential cooling solution that will have at least five times (5X) less climate impact than standard Residential/ Room Air Conditioners units in the market today with a total funding of 5 million USD. This technology could prevent up to 100 Giga tons of CO_2-equivalent emissions by 2050, and put the world on a pathway to mitigate up to 0.5˚C of global warming by 2100, all while enhancing living standards for people in developing countries around the globe. This challenge, currently in its final selection stage, saw more than 130 international teams from over 30 countries submit their innovative research ideas. Indian research teams registered nearly a third of the research proposal received under this program. This stands as an evidence to the efforts by DST during the last decade to facilitate national and international research networks in clean energy research.

CONCLUSION

India has taken several initiatives in the research of energy efficient buildings and technologies. The progress towards clean energy in habitat by DST through various research projects and programmes in the form of test facilities and prototypes have been accelerated. DST have totally invested 50 million USD towards clean energy research. DST has not only facilitated national research networks, but also cross-border international collaborations. Such initiatives have put India in a strategic position and global leader in clean energy research. The research outcomes of these programs are promising and ensure a promising headway in the area of energy efficiency. By understanding the need of the hour, researchers are involved in developing policies, prototypes, market ready products and technology solutions for building envelope, low energy cooling systems, lighting, automation and controls. The program aligns closely with The National Mission for Enhanced Energy Efficiency (NMEEE), which is one of the eight national missions under the National Action Plan on Climate Change (NAPCC), spearheaded by the

Bureau of Energy Efficiency (BEE). The outcomes of this research will complement the government of India's efforts to enhance energy efficiency in the demand side under the overall ambit of Energy Conservation Act 2001. Outcome will contribute to the regulation of building thermal performance and energy efficient operations. The efforts to build a clean, energy efficient habitat are opening up newer pathways for a sustainable future.

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PRE-DESIGN PERFORMANCE PARAPHERNALIA: IMPACT OF USING PRE-DESIGN ENERGY MODELLING TO GUIDE DESIGN DECISIONS

Shruti Shiva[1], Swati Puchalapalli[2]

[1]*Shruti Shiva*
Terra Viridis
Hyderabad, India
shruti@terraviridis.co.uk

[2]*Swati Puchalapalli*
Terra Viridis
Hyderabad, India
swati@terraviridis.co.in

ABSTRACT

Energy efficiency is often viewed as a function of building optimization. Various modeling software exist today that enable us to assess the energy performance of a building at schematic and detailed design stages. However, the implications of master-planning decisions at a conceptual design phase are yet underexplored. Be it its impact on microclimate or further building level performance, simulation based decision making at a conceptual phase is still at a nascent stage. This changing with the advent of powerful microclimate and urban performance assessors like ENVIMET and the ladybug-family.

This paper reviews early-stage building simulation tools and explains a methodology with a list of analysis metrics that help in making early stage design decisions from a practioner's perspective. In order to explain this further, the paper cites examples of various methodologies deployed ranging from, simpler microclimate studies like irradiation to complex evolutionary studies involving optimizing form on a selected project. This study uses literature as a starting point to cull tools relevant to the early design stage. Narrowing down to a set of four tools, namely –ladybug family, autodesk-flow, UMI, and envimet based on ease of use, design decisions to be made and running time. The paper uses a case study as a means to illustrate the application of the methodology of each tool while critiquing them from a usability perspective and practitioners view point. The paper concludes with the '3C principle' that endorses the use of these tools in early stage design development while hinting at a direction ahead. (250 words)

Keywords—Early design stage, Performance analysis, tool study, simulations, case study

INTRODUCTION

Energy efficiency is often viewed as a function of building optimization. Various modeling software exist in the market today that enable us to assess the energy performance of a building at a schematic and detailed design stage, Energyplus, IESve, EDSL TAS and Design Builder to name a few. While they enable us to perform detailed thermal and daylighting assessment at later stages, studies have revealed that optimization of buildings at early design stages is equally important. A seminal study conducted by Dr. P de Wilde(2004) of Delft University, included a survey of 76 green buildings in Europe (using 303 green building technologies) and its findings showed that 57% of these buildings had planning measures implemented in early stages.

Designing with early stage feedback, however, demands that real-world concerns, technical limitations and the now developing plural multidisciplinary nature of design are all addressed. Challenges like – time consuming simulations, frequent and rapid changes in design and planning in early stages, lack of methodology to implement intangible information, clashing and conflicting requirements of various consultants and input uncertainties (Han et al,2018), need to be tackled for early design simulation to become normative. This is changing with the advent of powerful microclimate and urban performance assessors like ENVIMET and the ladybug-family. Thus, this paper aims to provide a method to leverage these tools, describe their use in early-stage design and suggest the application of the these tools to evaluate early-design factors from a practitioner's perspective.

Aim:

The aim of this paper is to provide an insight into the use of a select set of simulations tools and methodologies of using these tools to make informed decisions for energy efficicny and comfort at an early design stage. The key research questions this paper seeks to answer are:

1. Why is the use of building simualtions to make early stage design decisions important?

2. What tools are available now and which analysis parameters should be considered for decision making.
3. What kind of design decisions could be made using these tools?
4. What are the challenges that present itself to the active adoption of early stage analysis?

Methodology:

- The paper screens and establishes a list of building simulation tools that are widely used internationally for early design stage decision making and their competence in addressing aforementioned points. The list of tools are critiqued based on the following.
- Ease of usability and nature of expertise required to use the tool (Engineer friendly, architect friendly etc.)
- Ability of tools to integrate design decisions, that is, compatibility with design or CAD software
- Factors of the environment that can be optimized and studied in the early stages and their consequence (energy performance, daylight, microclimate performance

This is followed proposing a methodology in the form of listing out the various analysis parameters to be considered during the early design stages, the tools available to study these parameters and the design decisions that could be taken based on the output of these tools. This methodology is futher elucidated using a case study. The paper concludes with a simple 3C principle that endorses the use and necessity of early stage analysis.

Scope and Limitations:

The paper focuses on the assessment of various tools' usability in early design phase; therefore, the algorithmic improvements made concerning their applications for building physics will not be discussed. While there are a plethora of tools that can be assessed, this paper limits the gamut of tools to those which have been applied widely from a practioner's perspective, so as to provide validation. The conditions presented are local to Indian cities, which can be extrapolated to similar climatic conditions elsewhere.

LITERATURE REVIEW

Background And Related Studies

Negendahl (2015) argues that while optimization focuses on quantitative rather than qualitative assessment, he adds that researchers "have sought to reconcile artistic control to optimize on predefined criteria with predefined constraints". This essentially implies that while optimization might be considered a numeric function of performance alone, it is now almost imperative to include a method for designers to exert subjective concerns to it too. Parameters outside of the realm of environment need to also be incorporated into optimization.

Hensen and Hopfe (2011) stated that to make design exploration computationally viable, the analysis of sensitive variables is a good starting point. This would give the designer an indication of what element is critical and what is not. To further speed up the process, Hopfe et al (2012) introduced surrogate models using a Gaussian process[1] to include qualitative parameters to mimic real life as much as possible. The use of surrogate models to include more and more random variables is a popular method to include subjectivity into optimization.

Many researchers furthered on this process to develop more methods that could decrease computational time and include adaptive precision. The development of integrated dynamic models coupled with visual programming languages and one or more performance analysis engines have made it easy even for non-developers to use analysis tools at early stages. One such system is the Ladybug family, which utilizes rhino as a base modeler, uses grasshopper to provide possibilities for design alteration parametrically, which in turn was fed by an environmental assessment engine like EnergyPlus. This will be discussed in more detail in the later sections of the paper.

Building Environmental Simulation Theory

The process of designing happens in stages and the widely followed process is – Pre-design, schematic and detailed. Each stage entails a specific scope of work and thereby, informs the amount and nature of information available at each stage.(Morbitzer et al,2001) As the early design stage is characterized by more variables and less certainty, the scope of optimization appears limited. However, a brief look at MacLeamy's curve (Fig 1) shows that decisions made in the early design stages have the maximum capacity to impact performance at minimum cost to changes made. The curve also indicates that a traditional design approach where maximum

[1] Gaussian process is defined as stochastic (randomized process) through which a finite collection of linear combinations are normally distributed.

optimization happens in the detail stages incurs more cost with lowered efficacy.

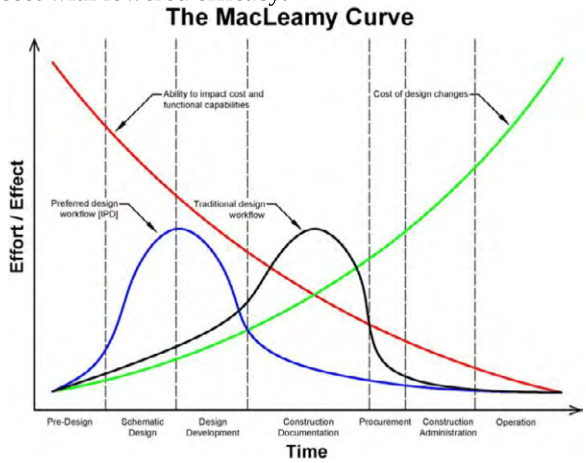

Fig 1: Macleamy curve-correlating stages of performance to cost and ability to make changes (source: Willis et al, 2014)

Attia et al. (2009) in their comprehensive assessment of building energy simulation tools which included a survey from end-users concluded that architects prioritize intelligence, ease of usability, and interoperability over accuracy and ability to simulate detailed building aspects. Therefore, rather than an exhaustive set of documentation to aid complex simulations, simplified indicative assessments are preferred. This helps us to further narrow down to parameters that become the lens through which the tools will be parsed through in the following section. These parameters are: ease of use, parametric capacities, adaptability, robustness to include real-life constraints, and relevance at early stage with limited information access.

Simulation Tool Types

In the building performance field, simulation tools can be divided into two aspects: Geometry generators and the simulation tool itself. Commonly used geometry tools used by both architects and performance analysts are: Rhino, SketchUp and Revit. Attaching themselves to each of these geometry generators are various simulation tools. Han et al.(2018) succinctly divide them into the following groups: 1) Simulation plugins for popular CAD tools 2) GUI for mature simulation engines. These include tools designed to create an easy interface between daunting engines like EnergyPlus and TRNSYS and the user. 3) Self-governing simulation tools. Fig 2 is a culmination of their review of various tools that fall under each category.

Software		Interoperability			Simulation Results						Functions		
		Design Tool	Simulation Engine	Interoperability	Energy	Thermal	Daylighting	Air Quality	LCC	Carbon Emission	Cloud	UA/SA/PA	Optimization
plugin	OpenStudio	SketchUp	E+ Radiance	File exchange	√	√	√	√	√			√	√
	HTB2	SketchUp	Own	File exchange	√					√		√	
	Sefaira	SketchUp Revit	E+	Run-time	√	√	√				√	√	√
	IES VE	Own Revit SketchUp	Own	File exchange	√	√	√	√	√				
	Green Building Studio	Revit	DOE2	File exchange	√		√			√	√		
	Grasshopper: Honeybee and Ladybug	Rhino	E+/OpenStudio Radiance/DAYSIM	File exchange	√	√	√						√
	Grasshopper: IEC bear	Rhino	Viper DIVA	File exchange	√	√	√						√
Independent tool	DesignBuilder	Own	E+	File exchange	√	√	√	√	√	√	√	√	√
	jEPlus (jESS)	Own	E+	Run-time	√						√	√	√
	N++	Own	E+	File exchange	√	√		√			√		
	Virtual Design Studio	Own	E+	File exchange	√	√		√					√
	ZEBO	None	E+	File exchange	√	√						√	
	Riuska	Own	DOE2	File exchange	√	√		√					
	iDbuild	Own	BC/ LC	Standalone	√	√	√	√				√	
	NewFacades	text	E+	File exchange	√		√						
	mkSchedule	SketchUp	E+ Radiance	File exchange	√		√						
	MIT advisor	text	Own	File exchange	√	√	√		√		√		

Fig 2: Comparative study of tools (Han et al, 2018)

Of the list, the tools with most application to the early design stage that are chosen for further study are honeybee/ladybug family of tools. This is owing to their plural application in outdoor studies, open source network and rapid advancements. This is also aided by Rhino's high interoperability with both CAD and sketchup (design tools preferred by architects in early stages). While Revit is also preferred for modelling due to its BIM compatibility, its optimization potential in early stages is fairly limited.

Along with them, independent tools such as Autodesk Flow (for wind studies), UMI - an urban tool developed by MIT lab and ENVIMET-outdoor/microclimate developed by Dr Micheal Bruse, will also be discussed due to their popularity and ease of use as for the former and their exhaustive computation capacity as is with the latter.

Description of Chosen Tools For Study

Ladybug Family: The ladybug/honeybee family of tools is a set of free open source grasshopper plugins that support a vast range of environmental analyses. This includes- Ladybug (early-design tool), Honeybee (detailed thermal and daylight modeling), Dragonfly (enable large scale masterplan calculations for heat island impact, microclimate analyses) and Butterfly (Leverages OPENFOAM for computer fluid dynamic studies at varying scales). Roudsari et al.(2013) exalt ladybug's openness, which allows for the democratization of environmentally conscious design processes. It is a parametric tool that operates with Rhino, allowing for a robust CAD interoperability. Its leverage of Energyplus, Radiance, Daysim and Openfoam engines in a simplified interface, with optimization capabilities has made it a very popular choice in recent years.

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When used in conjunction with other grasshopper native plugins, the ladybug family can perform iterative studies as well to optimize early design form. For instance, Galapagos and Octopus are evolutionary solvers that perform numerous iterations to optimize for a certain environmental parameter. Using both, one could optimize to increase daylight while iterating orientation options.

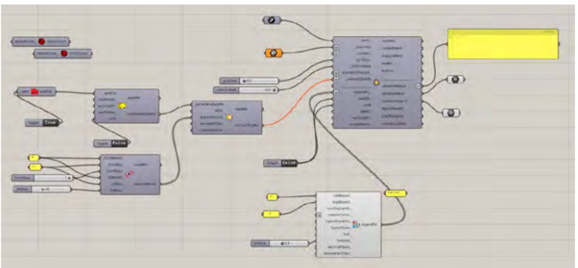


Fig 3: The ladybug interface/workflow on Grasshopper

Autodesk Flow design: A product of the Autodesk family, Flow design is basic wind flow analysis software that uses a virtual wind tunnel to simulate large scale, point-in-time airflow simulations. It uses Rhino compatible geometry, which would allow the user to make block models in rhino and run quick air flow simulations. While it is very useful to generate quick runs, during the iterative phase, it lacks the ability to compute the effect of niches, cut-outs and other wind flow promoting design elements.

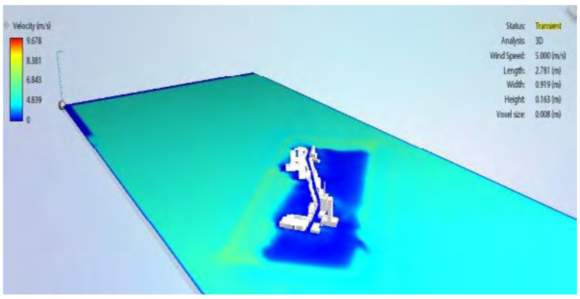


Fig 4: Flow design interface/Workflow

Urban Modeling Interface (UMI): Developed by the MIT sustainable lab, Urban modeling interface (UMI) is a grasshopper/rhino (fig.5) plugin that can be used to evaluate environmental performance of masterplans during early stages with respect to early energy use, walkability, schematic embodied use and daylight potential. Using EnergyPlus and Daysim as its primary engines, UMI performs quick analyses that enable comparative iterative studies between options at master planning stages.

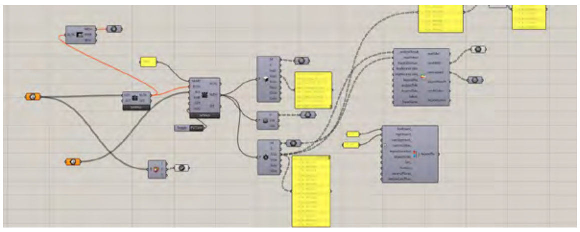


Fig 5: UMI workflow/interface on Grasshopper

ENVIMET: While a plethora of tools exist for indoor computations, ENVIMET currently holds an unchallenged status in being the most comprehensive outdoor study tool. ENVIMET, developed by Dr

Micheal and Prof Daniela Bruse, Envimet is an independent tool with its own modeling interface that performs detailed microclimate simulations, assessing the role of vegetation, water, the atmosphere, architecture and materials. The tools can be deployed at both macro (city) and micro (master-plan) levels. While it is the most exhaustive tool currently to account for outdoor performance, comfort and design, it is limited by its unique modeling interface, high-computation time and price. It is, however, slowly making its interface with grasshopper and ladybug possible.

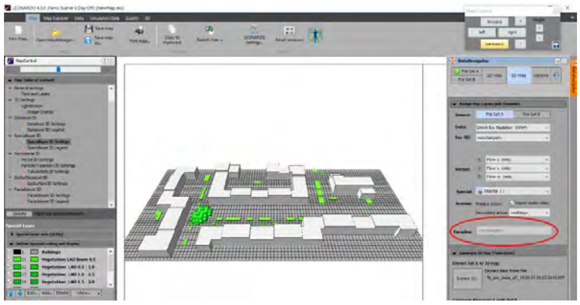


Fig 6: ENVIMET workflow and interface

Tool critique – Pros and Cons

This section is a summary of the features, appplications, pros and cons of the chosen tools of study.

Table 3: Ladybug tool-Critique

Ladybug	
Applications	Climate data analysis and display, outdoor comfort studies, irradiation studies, shadow studies.
Output	Visual data output-images, charts, graphs, and excel data
Input needed	EPW, simplified model
Pros	Comprehensive, easy to use, produces visually explicit images. Open source is an added advantage
Cons	As it uses EPW primarily, if a location does not have an established EPW file, data produced may not be accurate.
Run time	Varies - Few minutes for climate data to an hour or more for detailed models for irradiation

Table 4: Honeybee tool- Critique

Honeybee	
Applications	Microclimate mapping, early stage passive strategy consultant
Output	Visual data output-images, charts, graphs,

	and excel data
Input	EPW, model
Pros	Can be used for mapping PET across a site, accounts for vegetation and atmospheric features
Cons	Time consuming, does not account for water bodies
Run time	Time intensive

Table 5: Autodesk flow tool-critique

Autodesk flow design	
Applications	Wind flow mapping
Output	Images
Input	3DS or OBJ files of models
Pros	Quick, easy workflow
Cons	Cannot be used when model has cut-outs or niches, over-simplification and ignores eddy currents, not robust enough to handle varying types of Wind simulations. Paid and limited license. No longer being updated
Run time	Fast – a few seconds to a few minutes

Table 6: Butterfly tool-Critique

Butterfly	
Applications	Wind flow analyses, indoor and outdoor
Output	Files that need to be viewed in ParaView (interface for viewing Openfoam files)
Input	Simplified model in Rhino
Pros	Performs accurate, detailed wind flow simulations accounting for temperature as well
Cons	Installation might pose difficulties, results need to be viewed in a separate software, very time consuming.
Run time	Very time intensive – More than 6 hours. Takes 24 to 36 hours for more complex models

Table 7: UMI tool-critique

UMI	
Applications	Basic pre-design evaluation of Daylight potential, walkability and early energy performance.
Inputs	Simplified Rhino model
Output	Visual data output-images, charts, graphs, and excel data
Pros	Quick, simple to use
Cons	Assumptions and background processing is opaque, not very flexible
Run time	Fast – a few seconds to a few minutes

Table 8: ENVIMET tool-critique

Envimet	
Applications	Complete microclimate assessment, outdoor studies
Inputs	Model built on its bespoke modelling software, minimal climate data
Output	Graphs and charts on inbuilt viewer
Pros	Comprehensive, exhaustive analyses for microclimate
Cons	Minimum of 24 hour run-time produces results only for 24 hours, non-intuitive modelling interface. Learning curve is distinct and specific only to this software.

	Fairly expensive paid software.
Run time	24-72 hours depending on complexity of model

EARLY DESIGN STAGE METHODOLOGY

Before moving onto early design stage optimization methodology, it is vital to understand the parameters that can be optimized at various stages using simulations. Table 1 summarises them.

Table 1: Design Parameters impacted at different design stages while designing for Comfort and Energy Efficiency

Pre-design (Early Stage Design)	Schematic Design Stage	Detailed Design Stage
Orientation Shape and form Spacing and block height Floor plate depth Facade options Internal layouts Conditioning options (Natural, Mixed mode or Airconditioned) External spaces, entry ways and user experience Renewable energy potential and options	Façade Design for comfort, daylight design and solar control. Glazing and envelope design External Shading device design Interior layouts and furniture layouts Detail out space conditioning strategies (especially natural ventilation and mixed mode) Explorations of Mechanical systems (especially low energy systems) Electrical systems and RE integration Integration of firefighting requirements	Materiality of envelope and shading devices Structural integration of façade design Interior design Ceiling design Detailed M&E Engineering Detailed structural engineering

Table 2 illustrates the factors that could govern the optimization of design parameters listed in the pre-design stage.

It is also prudent to eliminate possibilities before simulating, to optimize for time. This can be done using simplistic thumb rules, such as:

1) Using Depth of floor plate thumb rule to avoid testing outlier conditions
2) Using weather data to pick only critical orientations for wind analysis
3) Using structural rules and maintenance requirements for eliminating unrealistic overhang depths.

This can then narrow the choices to be simulated and produce faster, relevant results. However, there is a danger of oversimplification using only thumb rules, and therefore must be used merely to reduce the pool of iterations and not make final design decisions.

Table 2: Inputs from Climate and Building Simulation Analysis that help in making design decisions during early design stages

For Climate Analysis		
Studies required to make early design decisions	**Tools that can be used**	**Design inputs can be given for the following**
Temperature & humidity –seasonal variations Adaptive comfort requirements Wind speed and direction Radiation intensity and distribution Sunpath and shading Ground temperature Impact of shading and wind on UTCI/PET	Ladybug Honeybee Climate Consultant Microsoft Excel	NV and mixed mode ventilation potential Passive design techniques to be incorporated Times of the day and year to provide shading Shading requirements for each façade Potential depth of floorplate based on built form Design requirements for open and semi-open spaces Renewable energy potential
For Orientation, Form, Depth of Floorplate, Spacing & Height		
Solar irradiation Wind flow Daylight availability and ingress	Ladybug Autodesk flow Butterfly Honeybee UMI	Optimum orientation, block shape and form Spacing between blocks for various orientations to balance self-shading and daylight
For Envelope and Interior Layouts		
Solar irradiation on surfaces Sun path and shading angles Daylight availability and ingress Wind flow Natural ventilation distribution Mixed mode ventilation strategies	Ladybug Autodesk flow Butterfly Honeybee UMI Sun path and Shading Overlays Rules of thumb for daylighting and natural ventilation	Façade design requirements for solar control, glare and usable daylight Fenestration location, size and geometry for natural ventilation and daylight integration Interior layouts based on daylight availability and thermal comfort Shading requirements for glazing
For Microclimate and Buffer Spaces		
Solar irradiation Wind flow External and semi external space comfort conditions (PET and UTCI)	Ladybug Autodesk flow Butterfly Honeybee	Pedestrian comfort requirements Entryways, External and semi external space design
		requirements Landscape requirements Site level requirements to enhance natural ventilation and cooling potential Solar PV location and sizing

CASE STUDY

This section uses a case study to demonstrate the use of the tools and methodology proposed in the paper, as per practice. The study aims to validate and give a purport of the above sections by citing inputs that were given to the architects/designer.

Project details:

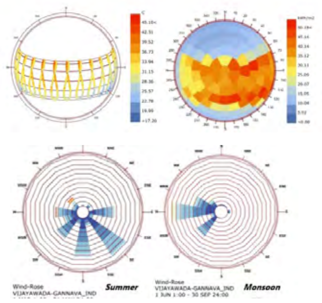
Ascendas Catalytic development (Winning Competition Entry)

Residential-Commercial mixed use complex

Design Team: Architect Hafeez Contractor, TerraViridis

Location: Vijayawada, Andhra Pradesh (Warm & humid climate type)

Step 1: Climate analysis



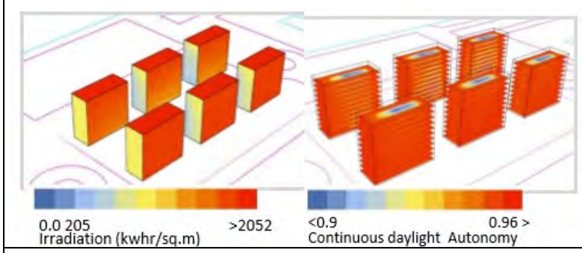
Analysis performed: Culling of numerous weather data which includes extracting annual temperatures, rainfall, wind speed and directions, radiation rose and PET.

Software used: Ladybug, Excel

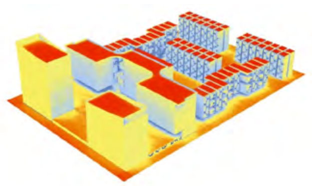
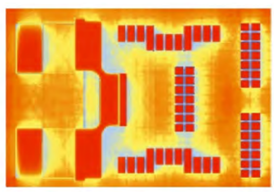
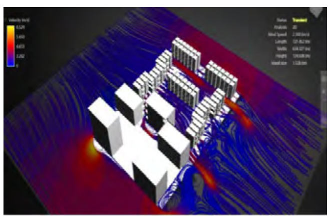
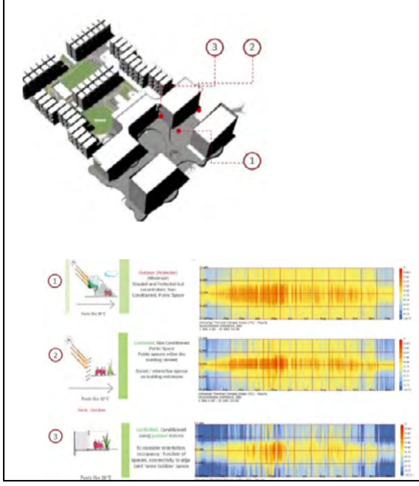
Design input provided:

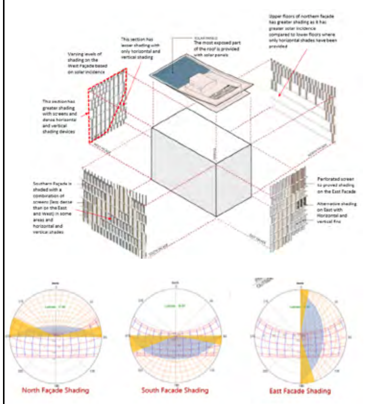
Mixed mode Ventilation potential, Passive design strategies, Shading requirement, Optimum orientation for wind and sun, low energy cooling options

Step 2: Parametric runs



Analysis performed: Parametric runs to optimize block spacing for various orientation and certain heights for

<table>
<tr><td colspan="2">balancing daylight and self-shading
Daylight ingress for defining floor plate depth
Sensitivity of orientation on solar irradiation</td></tr>
<tr><td colspan="2">Software used: Ladybug Galapagos, Daylight thumb rules
Design input provided:
Optimum depth of floor plate and spacing between blocks provided for different heights and orientations
Optimal orientations for blocks</td></tr>
<tr><td colspan="2">Step 3: Masterplan studies</td></tr>
<tr><td>

</td><td>Analysis performed:
Irradiation for both building and ground plane
Wind flow analysis
Software used:
Ladybug for Irradiation
Flow design for wind
Design input provided:
Tweaking block design to balance self-shading with daylighting</td></tr>
<tr><td colspan="2">Input for block design to enhance wind flow through the site, both at pedestrian levels and higher elevations to maximise pedestrian comfort and natural ventilation/cooling potential
Inputs for façade design based on irradiation and solar shading requirements</td></tr>
<tr><td colspan="2">Step 4: External comfort/outdoor studies
</td></tr>
</table>

<table>
<tr><td colspan="2">Analysis performed: Outdoor comfort studies based on UTCI metric for various spots on the masterplan
Software used: Ladybug</td></tr>
<tr><td colspan="2">Design input provided:
Location and nature of required outdoor architectural elements provided. E.g. Vegetative grove for shading in uncomfortable spots, shaded walkway and seating location</td></tr>
<tr><td colspan="2">Step 5: Façade recommendations</td></tr>
<tr><td></td><td>Analysis performed:
Shading and radiation analysis for façade recommendations
Software used:
Ladybug + Sun path and Shading overlays</td></tr>
<tr><td colspan="2">Design input provided:
Complete façade requirements and articulation for every façade for solar control, daylight, views out and comfort</td></tr>
</table>

CONCLUSION & INFERENCES

The advent of powerful, streamlined simulation tools and its graphic results shows that the foray into the world of early stage design decision making simulations tools is progressing well. With the help of the case study above, we can demonstraste that dynamic tools interfacing with CAD based design tools are very effective in providing timely and useful input for early stage design decision making for energy efficiency and comfort. While their challenges are also obvious, their essentiality can be summarised through the following lenses or what can be called – the 3C principle:

1) Cost: The cost of performance optimization at later stages is real and proven as shown in the Macleamy curve. While a design is in the early stages, it is robust and resilient to frequent changes. Changes and optimization in later design stages causes issues with design integration and overall desing optimisation. During construction phases, it would incur more costs. For instance, if the block design is such that solar exposure is high and natural cooling is low, it will require greater control at the façade

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level to ensure energy efficincy is achived. This would, more often than not, incur extra expenditure with limited results and would also compromise on comfort and/or views out. Whereas, if a preliminary assessment of sunpath, radiation and wind flow are taken into consideration during early design stage, orientation and/or form changes could be explored at no added cost.

2) Connected/customisable: The initial learning curve to operate the Ladybug family might seem daunting. It requires one to familiarize with the grasshopper interface and that has in its early releases, dissuaded many. However, being an open source tool, the support one recieves through its ever expanding online community is exhaustive. People from around the world using these tools can solve problems one might encounter while performing analysis on a real-time basis. Additionally, as it is open source, it is inherently customisable and can be tailored to solve your specific goals.

3) Creative: The interoperability of a tool with Cad interfaces is essential in determning its success as an early stage analysis tool, as most designers still prefer the CAD envrionment during early stages for design. Tools that allow for paramteric studies and a back-and-forth motion between analysis and design implementation, are bound for increased usability.

On-going research

The field of early stage analysis is only headed for greater exploration. The next trend that is observed is the integration of cost implications of early design decisions and a refined sensitivity perspective with respect to the role of each architectural element in the final performance outcome. One such paid tool is the Cove tool (cove.tool,2019). The tool provides fast and graphic results connecting paramteric studies to cost and peformance, albiet using gross oversimplifications. The interface of Design explorer (Thornton Tomasetti, 2019) allows for users to see a very clear cut connection between iterative studies, results and subsequently, help pick the better results. Both these tools find themselves in the grasshopper world as well, owing to the growing popularity of the platform amongst designers as well.

Limitations to the use of Early design Stage Tools in India

Most often, architects are unaware of the design input that is possible from these tools and even when these tools are used during the early design stage, they are unable to convert the inference to effective design decisions. This, combined with very tight project times lines has resulted in these tools being used more for visualisation and post rationalisation of a developed design.

In order to mainstream the use of these tools in the interest of energy efficiency, training and capacity building through profesisonal development programs and integration into Architecure curriculam is key.

Another important matter to address is the choice of the right tool for a certain task. With the number of tools available presently and new ones being added continuously, it would be important for users to not only understand what a simulation tool can do but also its' limitations in order to make effective and correct design decisions within the timeline available.

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CHARACTERISING COMMON AREA ENERGY USE TO ASSESS CLEAN ENERGY OPPORTUNITIES IN APARTMENT COMPLEXES OF BENGALURU

Sumedha Malaviya[1], Sumathy Krishnan[2] , Santhosh Cibi[3] and Ravichandran K[4]

[1]*Energy Program, World Resources Institute India*
World Resources Institute India
Bangalore, India
sumedha.malaviya@wri.org

[4]*Technology Informatics and Design Endeavour (TIDE) India*
Technology Informatics and Design Endeavour (TIDE) India
Bangalore, India
ravi.k@tide-india.org

[2] *Technology Informatics and Design Endeavour (TIDE) India*
Technology Informatics and Design Endeavour (TIDE) India
Bangalore, India
k.sumathy@tide-india.org

[3] *Technology Informatics and Design Endeavour (TIDE) India*
Technology Informatics and Design Endeavour (TIDE) India
Bangalore, India
santhosh.cibi@tide-india.org

ABSTRACT

Residential building stock was estimated to be 15.3 billion m^2 in 2018 and is projected to reach 28.4 billion m^2 by 2030. While there are no public datasets available on the typologies of residential buildings in Indian cities, the visibly changing skylines of cities like Bengaluru, Pune, Gurugram and Hyderabad clearly highlight the affinity towards multi-storey apartment buildings. Property trends in Bangalore indicate that builders will continue to construct new apartment complexes every year. The significant energy-related carbon footprint of these buildings requires deeper investigation to quantify and characterize demand and assess feasible options to mitigate emissions.

Common areas represent aggregate demand for energy services shared by several households. Depending on their feasibility, clean energy - energy efficiency (EE) and on-site rooftop solar (RTS) interventions can reduce carbon emissions from common areas. We studied energy used for common services in ten apartment complexes and characterized consumption by services (e.g. pumping, lighting), identified EE measures to reduce consumption and explored possibilities of meeting demand through on-site RTS. We found that conservative application of EE measures alone can save energy from 5 to 20% in different apartment complexes depending on the efficiencies of existing equipment and technoeconomic feasibility.

The study found that, it was possible for existing apartment complexes to significantly lower carbon emissions through clean energy if they overcame management, technical and behavioral barriers. Additionally, such evidence-based studies of common energy services can help inform policies and regulations on the design and development of new energy efficient apartment buildings in Bengaluru and other cities.

Keywords—Apartment complexes, common area energy, energy efficiency, rooftop solar, Apartment Owners Associations

INTRODUCTION

In major cities, land constraints and favourable regulations on Floor Space Indices (FSIs) are encouraging development of high-rise, multi-storey apartment complexes, frequently gated in cities like Bengaluru, Gurugram and Pune. As on May 2019, a property website listed 2239 apartments for sale in Bangalore, 32% of which were in high-rise apartment complexes (those with a height of more than 15 meters or roughly ground floor plus four floors as per the BBMP definition) and the remaining in low to medium-rise apartment complexes. These gated residential communities provide all facilities and services that city residents expect from the government- 24/7 power and water supply, clean and safe streets and recreational spaces. Provisioned privately by the developer, through common services, these amenities have an unknown energy and carbon footprint.

While data on the number and the growth of different types of residential buildings is scattered at the national and local levels or unavailable, visiblly changing built environment in large cities indicates a propensity towards multi-storey residential apartments. Given the growth of this type of residential construction, characterizing energy used in common services is a necessary first step. In 2014 and 2016, with the launch of two guidelines on the design of energy-efficient multistory residential buildings for composite, hot-dry climates and warm-humid climates respectively, the Bureau of Energy Efficiency (BEE) indicated its intention to address energy use in apartment buildings (BEE 2014 and 2016) The guidance was based on data from one apartment building in Delhi with 90 flats in which elevators, lighting, and water pumping were found to consume 62 percent, 21 percent, and 17 percent of total electricity use, respectively. These guidelines present the only published data on energy used in common services from an Indian city.

If this data were to be collected for a larger sample in Indian cities, where should one start and what should be the methodology? Is there a role for apartment buildings in meeting the 40GW rooftop solar target of the government? What barriers and opportunities exist on the ground to implement clean energy interventions (energy efficiency and renewable energy) in existing apartment complexes? These were some of the research questions explored in our study primarily aimed at assessing clean energy opportunities for existing apartment complexes through characterising common area energy use.

This paper describes the process of engagement with ten apartment complexes in Bangalore on collecting energy use data, through which we also created awareness about energy efficiency and renewable enegry measures and facilitated planning and decision making on clean energy projects by apartment owners associations (AOAs). The process could be similar in other cities and for similar bodies or associations of residents like Resident Welfare Associations (RWAs). The paper can inform development programs and schemes to implementing clean energy projects for apartment communities.

LITERATURE REVIEW

Apartment building stock data: The office of European statistics (EuroStat) collects information annually from EU member countries on a range of datasets including number of flats, number of flats in a building with ten or more or less than ten dwellings. In the US, the American Housing Survey collects data on the number of apartments which are further characterised based on number of bedrooms, amenities offered (central AC, dishwasher, washing machines and dryers) and number of apartments in the building or the complex.

In India, the census collects data on the number of households as per different room categories: non-exclusive room, one room, two rooms, three rooms, four rooms and five rooms and above. This information however is not collected as per the type of dwelling unit i.e. independent or detached houses, apartments or flats in complexes. A breakdown of residential building stock into different types is necessary for urban planning, resource planning and assessing implications on resource use from the demand side. At the city level, while a centralized database of building stock and its constituents doesn't exist (it is typically disaggregated or scattered across multiple revenue offices of the municipality), some municipal corporations, do provide statistics on the building plans approved and occupancy certificates provided as per building type on their websites. In Bangalore, the town and country planning (TCP) provides this information on the Bruhat Bangalore Mahanagara palike (BBMP) website. Between 2014 and 2019, in North and South Bengaluru alone close to 500 apartment complexes that were handed occupancy certificates.

Management of apartment buildings: The ownership and management models of apartment complexes determines how clean energy projects for common areas will be implemented and managed. In a review conducted as a part of the European project Low Energy Apartment Futures (LEAF) on ''Improving the energy efficiency of apartment blocks 'the following observations were made by the team on management of apartment buildings in different European countries (LEAF 2016).

- Depending on the legal requirements, existing political system, different countries have resorted to different formats for managing common areas in multi-apartment housing complexes.
- Some of these vary in terms of the legal requirement- mandatory (e.g. Czchec republic) versus voluntary associations or based on ownership structures- associations working with professional private facilities management companies or management

completely delegated to private companies (e.g. US).

- There are also differences in the level of regulation of associations, some having established procedures for constitution and decision making (e.g. US and Western European countries) or rules pertaining to collection of funds for maintenance and servicing.
- In Russia, associations and memberships to them are not mandatory creating a situation where decision-making becomes difficult and can create conflicts, also impacting access to financing for refurbishments or retrofit projects.

In Australia, Owners Corporations or bodies corporate are created to manage and maintain shared or common property; with territories and states enacting their own legislations to guide the working of these entities (FMA Australia 2012)

In India, depending on the state, laws exist for the registration of associations that manage apartment complexes. In Bangalore, most Apartment Owners Associations (AOAs) are registered under the Karnataka's Registered Societies Act 1960. AOAs should be ideally registered either under Karnataka Co-operative Societies Act, 1959 or Karnataka Apartment Ownership Act (KAOA), 1972. However due to the absence of an authority to oversee and resolve issues faced by apartment complexes, AOAs have not registered under the KAOA 1972. AOAs are formed by 7 or more owners of the apartment building by applying to the Karnataka registrar of societies. Collectively all the members of the association make up the General Body (GB) of the association. The GB has the final authority with regards to formulation of the association bye-laws and key decisions pertaining to spending of maintenance budget and corpus money. Members from within the GB can volunteer to become part of the Management Committee (MC) which has a term of at least 2 years.

Common area services: In the US, the National Apartments Association defines common-use areas as those that as *areas that are made available for the residents of a building and their guests including hallways, lounges, lobbies, laundry rooms, refuse rooms, mailrooms, recreational areas, walks and breezeways*. In Australia, what constitutes as common area varies depending on the states and territories. In Europe also, common area definitions vary in different countries typically explained in the rules and regulations governing creation of apartment associations and building bye-laws.

Common services are not defined in India's National Building Code. In BBMP's bye-laws, common services are not directly but Section 9.10.3 describes *the floor area of a building shall be the aggregate area of the floors of all parts of the building including thickness of walls, parking area, staircase rooms, lift rooms, ramps, escalators, machine rooms, balconies, ducts including sanitary ducts, water tanks, lobbies, corridors, foyers and such other parts provided for common service*. In Karnataka's Apartment Owners Act 1972, common services are defined comprehensively as facilities including- (*1) the land on which the building is located; (2) the foundations, columns, girders, beams, supports, main walls, roofs, halls, corridors, lobbies, stairs, stairways, fire-escapes ,entrances and exits of the building; (3) the basements, cellars, yards, gardens, parking areas and storage spaces; (4) the premises for the lodging of janitors or persons employed for the management of the property; (5) installations of central services, such as power, light, gas, hot and cold water, heating, refrigeration, air-conditioning and incinerating; (6) the elevators, tanks, pumps, motors, fans, compressors, ducts and in general all apparatus and installations existing for common use; (7) such community and commercial facilities as may be provided for in the Declaration; and (8) all other parts of the property necessary or convenient to its existence, maintenance and safety, or normally in common use.* While it is still uncommon for apartment complexes to provide centralized hot water or cooling in India, some new residential developments in Bangalore are being designed to provide these services.

Decision making on clean energy projects for common areas: In a review of decision-making on clean energy projects for multi-family housing in European countries, Matschoss et al (2013) highlight the following (1) decisions to implement energy efficiency retrofits or renewable energy projects may be taken by the home owners association in countries like France, Germany and Spain, but bank financing requires all apartment owners to mortgage their apartments for the loan (2) the decision to invest in the project need the vote of at least 50% of the apartment owners (3) in Spain, for renewable energy projects, a majority of 30% is acceptable but those voting against cannot be charged for the project.

In the US, apartment associations, also called condo associations can levy a fee on apartments to pay for clean energy projects or finance it from the condo association. Based on the prevailing law in the state, decision making by condo associations for projects varies. In Massachusetts for example, decisions related to a condominium's common areas and funds are made by the trustees, which are elected by the condonium owners but approval for ''improvement'' projects (e.g. solar rooftop) requires vote from apartment owners (DOER 2015).

In Bangalore, AOAs tend to fund smaller sized projects from maintenance budgets while projects requiring significant investment are funded from a corpus funds and decisions to use this fund have to be taken by a majority of the AOA members in a general body meeting. These processes are usually described in the bye-laws of the apartment complex.

Clean energy programs for common areas: In Europe and the US, programs to introduce clean energy, particularly energy efficiency retrofits in existing apartment buildings have been driven by varied agents. Utilities have offered incentive programs for energy efficiency retrofits in common areas of multi-family housing or apartment complexes. Since apartment residents typically pay only for the utility cost of common areas, utilities have rolled out customized incentives only for EE retrofit projects. For example, DTE Energy offers incentives for common-area retrofits for energy efficient indoor and outdoor lighting (LED replacing CFL or halogen lamps and lighting controls), HVAC systems, room ACs, hot water systems, structural retrofits like energy efficient glass, doors and windows and discounted maintenance services (DTE Energy 2019).

In Germany, there is mandatory renovation fund (1 % of value of building) to have funds to do renovations (Matschoss et al. 2013). In Europe, Energy Performance Contracts (EPCs) are the most common vehicle for introducing energy efficiency retrofits. Under the EU's LEAF project, 15 apartment buildings in six European countries were identified as case studies to demonstrate the Energy Performance Contract (EPC) model for energy efficiency retrofits. It was concluded that EPC models covering whole buildings including common areas are needed.

In India, with the support of Shakti Sustainable Energy Foundation, Thane Municipal Corporation launched a guidebook on implementation of clean energy projects in high-rise residential apartment buildings in 2016. The guidebook provided technical descriptions of EE and RE measures that could be implemented. There are examples of apartment associations undertaking implementation of energy efficiency retrofits or implementing solar PV for meeting common area energy needs in Indian cities (Table 1).

Table 1: Examples of EE and RTS projects implemented for common areas in apartment buildings

Name of Apartment	Location	Number of Apartments	RE/EE Interventions Adopted	Impacts or Implications	Sources
ARK Serene County	Bengaluru	NA	106 kWp rooftop solar PV	Monthly electricity bill reduction of up to 25%	Mehrotra 2019b
Brigade Petunia	Bengaluru	49	96 kWp rooftop solar installed, with a break-even period of 7 years of 16% (internal rate of return)	In September 2018, apartment complex achieved zero electricity bills for common areas as 100% needs were met by rooftop solar	Solarify 2019
Mittal Auriga	Bengaluru	12	10 kWp for common services and an additional 10 kWp for power backup	Bengaluru's only carbon-neutral apartment complex. Monthly energy savings of 4,000 units in total for apartments and common area energy use and monthly bill savings of INR 10,000	Smarter Dharma 2019
Woodstock	Bengaluru	63	10 kWp for common services	Monthly electricity bill savings of INR 10,000	Solarify 2017
Mantri Astra	Bengaluru	149	20 kWp rooftop solar for common services	Monthly electricity bill savings of 10%	Mehrotra 2019a
Chartered Coronet Apartments	Bengaluru	NA	20 kWp rooftop solar for common services	Projected monthly electricity bill savings of INR 16,000 to Rs. 18,000	Mehrotra 2019a
Raheja Eternity	Mumbai	229	EE measures like LED bulbs and motion sensors for lighting in stairways and parking areas. Also implemented 85 kWp rooftop solar PV	40% reduction in energy use. Summer electricity bill down from INR 359,000 to INR 5,000	Sakaria 2017
Lunkad Sky Lounge Society	Pune	NA	12 kWp of rooftop solar	Rooftop solar meets about 47% of the energy consumed for water pumping	GKSPL and Prayas(Energy) group 2017
Royal Orange County	Pune	NA	20 kWp SPV system and 104 m^2 of solar water heater installed on one of the towers, which is 11 stories high and has 44 flats. All flats in the tower have both SPV and grid electricity	The free supply from the SPV system flat is fixed at 300 W per flat. Residents have incentive to conserve energy and make energy-efficient choices.	GKSPL and Prayas(Energy) group 2017
3-story building in Najafgarh	Delhi	NA	7 kWp rooftop solar with battery backup	Estimated payback period of 11–13 years	GKSPL and Prayas(Energy) group 2017

APPROACH

While our primary objective was to assess possibilities for EE and RE measures for common areas we had to first understand energy consumption in common areas. Understanding energy use, behaviour and operational patterns is the first step as per Buffington's Energy Pyramid (Figure 1) At present there is no official process or standardized methodology to understand and manage common area energy use. Our findings from Bangalore indicated that energy bills account for between 40 and 25% of the annual maintenance costs for apartment complexes. We designed designed to be simple and easy-to-use by facility supervisors and managers who typically have limited training and technical qualifications to conduct detailed energy audits.

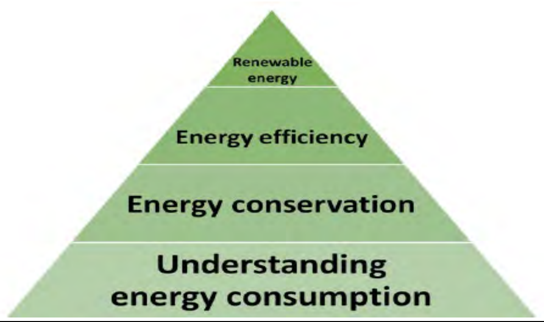

Figure 1: The energy pyramid (Source: Buffington 2010)

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Identification of apartment complexes: Access and entry into apartment complexes for the purposes of data collection needed permission from AOAs.

Table 2: Characteristics of the ten apartment complexes studied (Source: Authors)

Sl.no	Building Name, Location, Year of possession	Number of floors and towers	Number of flats	Common facilities in addition to common area lighting, pumping and elevators
1	A1 Hebbal 2011	5 floors 1 tower	40	Clubhouse Gym Play area Tennis Court Community Hall
2	A2 Malleshwaram 1986	9 floors 3 towers	96	None
3	A3, Hebbal, 2004	4 floors 13 towers	171	Clubhouse Gym Swimming Pool Play area
4	A4 JP Nagar 2007	16 floors 1 tower	190	Clubhouse Gym Swimming Pool Play area Tennis court Meditation Hall Indoor Games Badminton court
5	A5 Harohalli 2012	16 floors 3 towers	202 (and 26 row houses)	Clubhouse Gym Swimming Pool Play area Tennis Court Indoor Games Meditation Hall Library
6	A6 Doddenakundi 2010	12 floors 10 towers	387 flats	Clubhouse Gym Play area Tennis Court Basketball court Indoor Games Swimming Pool Badminton court
7	A7 BTM 2nd Stage 2008	18 floors 3 towers	402 flats	Clubhouse Gym Swimming Pool Play area Tennis court Basketball court Badminton court Indoor Games
8	A8 Jallahali 2008	11 floors 14 towers	482 flats	Clubhouse Gym Swimming Pool Play area Tennis/badminton court Meditation Hall Indoor Games
9	A9 RT Nagar 2002	9 floors 10 towers	600 flats	Clubhouse Gym Swimming Pool Play area Tennis Court Indoor Games Meditation Hall
10	A10 JP Nagar 2010	19 floors 19 towers	1573 flats	Clubhouse Basketball court Swimming Pool Play area Tennis/badminton court Gym Indoor Games

Based on this criterion, an initial list of 35 apartment complexes in Bangalore where either a resident or an AOA member was known to the study team was prepared. The study team reached out to their points of contact in the initial list, sought their interest and willingness to facilitate data collection from their apartment complexes.

For at least five apartment complexes, we conducted ''pitch presentations'', a meeting with the MC of AOAs to introduce the concept of addressing common area energy use and assistance offered by the team to implement any potential recommendation on clean energy measures. This process of getting apartment complexes on-board for sharing data took close to three months after which there were ten apartment complexes of different sizes and geographic spread (in different parts of Bangalore) willing to participate in our study and share data.

Data collection: Energy in common services is consumed in the form of (1) electricity that powers all electrical assets and equipment and (2) diesel that powers the diesel generator sets which function as back-up power in case of outages. To build a complete picture of energy used in common services we identified energy consumption data (electricity bills for all meters) and list of electrical assets and equipment as most critical. A template was prepared to collect data from AOA Management Committee (MC) member and or the building supervisors. Starting with an initial listing of core common services like lighting, pumping and elevators, that are common across all apartment buildings, we expanded our list of services and amenities that need energy, based on walkthrough assessments and interactions with supervisors of the ten apartment buildings. It was challenging to collect all the data in one visit. We conducted several visits and discussions with building supervisors, electricians and plumbers to get a complete profile of common area energy use in ten apartment complexes. In addition to the energy use profile we also tried to collect data on total size of common area in m^2 but could not arrive at reliable figures.

Table 3:Data collected on common area energy use and their sources (Source: Authors)

Category	Type of data	Data source
DISCOM assets	The number and location of electricity meters that supply power to common services; number of transformers with their rated capacities	Walkthrough assessments and interactions with supervisors
Electrical assets in common area	The list of electrical equipment and appliances with their number, power ratings and usage, a mapping of the number and type of equipment connected to each utility meter and the number and size of diesel generators (kVA).	Walkthrough assessments with supervisor/manager/maintenance staff
Electricity consumption by service category	Annual electricity bills of 3 years; Usage or number of hours of operation of electrical equipment and appliance	Copies of monthly electricity bills obtained from supervisors for each utility meter. We also approached the DISCOM with the account IDs of the meters to get billing data directly in case of data gaps; usage or number of hours of operation of each equipment and appliance was shared by supervisor
Diesel consumption	Number, size/capacity of Diesel generator (DG) set; annual or monthly use of diesel	Logs of diesel use shared by building supervisors and walkthrough observations of meters on DG sets
Others	Size of rooftop solar installation (if any); any records of annual maintenance of equipment and appliances	Any manual records kept by the supervisors

Some of the challenges faced are described below:

- In most complexes, there was a general lack of record keeping on electricity use, operational hours, maintenance of equipment and troubleshooting (e.g. number if times the motor of pumps had been rewinded)
- There is no method of recording annual electricity bills or tracking consumption.
- Where automatic water level controllers were used, getting data on hours of operation of pumps was challenging. We relied on hours of usage and rated capacity for non-submersible pumps as reported by the supervisors. For submersible pumps, rated capacties were difficult to record.
- Logs of diesel used in Diesel Generators, were either missing or were incomplete. Even where DGs had in-built meters, we found that these were not calibrated, their data was not recorded or were malfuncitoning.
- There were multiple LT meters connected to several equipment; in very few cases were there exclusive metering for equipment (e.g. only elevators or only pumps). The meters were distributed across apartment blocks or towers. There were cases where the same LT meter was connected to assets or equipment across two separate apartment blocks. For some assets, supervisors were unclear which meters they are connected to. Since we did not conduct detailed energy audits for all equipment, a break-down of electricity consumption by service category for each apartment complex was difficult and was achieved for four out of the ten apartment complexes.
- To assess potential for rooftop solar PV (RTS), access to the terrace was forbidden by some societies. We relied on google maps to quantify roof area available for rooftop solar PV.

Engagement with apartment complexes: The AOAs are primary stakeholders for implementing clean energy projects for common areas. Typically, after one to two years of occupancy of the apartment building, developers relinquish control of maintenance and management of apartment buildings to the AOA. All apartment owners are members of the AOA, which is managed by the Management Committee (MC). Most AOAs function on the administrative model of requiring approvals from all (or a quorum) of the AOA MC members for any projects for common areas exceeding a certain budget.

The other important stakeholders are facility managers or supervisors including technical staff like electricians and plumbers. During our engagement with apartment complexes, we delved deeper into the role and infuence of these stakeholders in decision making. Figure 2 captures this understanding.

After the analysis of data and identifying potential recommendations to reduce energy use through energy efficiency and introduce rooftop solar PV to meet a portion of the energy needs, we scheduled meetings with the AOA MC members to communicate the findings. For each apartment complex a report was prepared describing the recommended measures and associated economics.

In each apartment complex, we identified champions for promoting the cause of clean energy. These were both ordinary residents and MC members. We built their capacity to inform decision making by providing them with strong analysis Several rounds of meetings were conducted with the MC members to encourage adoption of recommendations.

Table 4: Primary stakeholders and their influence on decision-making on clean energy projects (Source: Authors)

Stakeholders	Description and Influence

Members of the AOA	• All apartment owners are members of the AOA and tenants are executive members. Members of the AOA weigh in on decisions that involve substantial expenditure for projects in the common areas.
	• Members of the AOAs play a key role in the decision-making process of implementing clean energy projects. This could mean:
	  ○ Consent to the use of maintenance budget or corpus fund towards project proposals for put forward by the MC at the project discussion meetings
	  ○ Or approving rules and regulations regarding reduction of end energy usage through changes in usage patterns (like drives to reduce lighting in common areas after a certain time of day) put forward by the MC.

Management Committee (MC) of AOA	• The members of the MC are the starting point for clean energy measures to be implemented. They take the initiative of sifting through and prioritising issues relating to the maintenance of the Apartment complex • Once the MC has narrowed down on a measure that they wish to implement, they begin by making an informed assessment of costs and benefits the proposal. This involves gathering information regarding the measure, selecting potential vendors (in most cases at least 3) and assessing the budget required for implementation. If the budget required is significant (exceeds a certain amount stipulated in the AOAs bye-laws) then they will need to convince residents during a General Body meeting to approve budgetary allocations. • Additionally, the MC members can undertake initiatives that address usage patterns, for instance drives to educate residents about switching off the lights and fans when the enter/exit the elevators.
Facility managers or supervisors	• Responsible for O&M of electrical appliances and utilities. They can aide (by volunteering their technical know-how and agreeing to educate themselves about maintaining new EE/RE technology) or hinder (by being uncooperative or providing incorrect analysis of equipment efficiency) the implementation and effectiveness of RE/EE measures.

To facilitate this, we shared list of EE and RTS vendors and service providers, scheduled meetings and discussions with providers willing to work in with AOAs.

Figure 2: Engagement process and some recommended measures to apartment complexes (Source: Authors)

In two apartment complexes, recommendations on LED lighting were implemented, one complex changed some of its old pumps and one installed a rooftop solar PV system for common area energy needs.

CONCLUSIONS

The process of collecting data on common area energy use was time consuming and made more challenging due to absence of standardized templates or methodologies. The approach we developed was intended to be simple, that could be easily adopted and implemented by facility supervisors who lack the technical training and resources to do in-depth energy audit studies. Our approach tries to demonstrate a methodology for establishing baselines and continouse monitoring of energy use in a systematic way. Some key implications of this research for policy making are described below:

- The forthcoming Energy Conservation Building Code (ECBC) for residential buildings is expected to prescribe energy efficiency measures and on-site renewable energy generation requirements for common area amenities. While these will prove to be useful guidance for new apartment complexes, for existing buildings, more data and characterisation of common area energy use is necessary, with a representative sample of apartment complexes with varied sizes and types of amenities. Any policy impetus must address the degree of difficulty in different types of retrofit projects. For example while changing elevators will save a lot of energy, it is not practical to implement and other smaller retrofit measures like change in controls, sensors can be explored.

- Also, given the variations in the size of the complexes, the number of amenities, overall layout of the complex, number of flats, developing a metric for comparison of energy used in common areas in apartment complexes can be difficult. But with larger sample sizes, this challenge can be overcome, and a common metric can be developed.

Barriers to clean energy project implementation: The existence of AOAs enables an organized process of decision-making on projects of common interest to the residents. As single entities managing common area services, AOAs offer the opportunity for collective decision making which does not face the common barrier related to split-incentives. Since any reduction in energy bills benefits all residents by reduction in maintenance charges. Also all the ten apartment complexes had a person designated as ‘’manager’’ which is a good sign for potential interventions. However there some key barriers that must be overcome to ensure that apartment complexes become strong participants in the clean energy transition:

- The EE and RE vendors we engaged during the process of project facilitation highlighted the long process of decision making as the major barrier for them to work with AOAs. This is a barrier not unique to Bangalore. In European countries the lack of agreement or acceptance amongst members of the association is a major barrier that takes precedence over technical or financial barriers. To overcome this, experts in Austria have suggested presence of a legislation that mandates retrofit projects or setting requirements in bye-laws of associations on a minimum obligatory reserve fund for clean energy projects based on the baseline energy performance of common area services like water pumping and lighting (Matschoss et al. 2013).

- During our interactions with AOA MC members to discuss the findings and recommendations, we observed that information must be made available in multiple formats, categorized into low or no cost, medium cost and high cost interventions with the economic analysis accompanying these interventions. Best practice guidebooks and toolkits must be made available to apartment complexes to enable informed decision making.

- The ten apartment complexes we engaged with did not highlight lack of financing as a major barrier. If AOA MC members are convinced about the benefits of the project, funds can be raised. Taking loans for specific projects was unheard of. However this may not be true for all apartment complexes. Since AOAs are formal associations

- In apartment complexes we engaged with, other issues like waste management, improvement and upkeep of clubhouses and swimming pools takes priority. Energy is considered as a supply side problem and diesel generators provide back-up incase of power outages. Also common area amenities are billed under domestic tariff category, significantly reducing incentives to save energy.

- Depending on the size of the apartment complex and the types and sizes of amenities operational, an investment grade energy audit can be a useful. Incentives on energy audits can be offered by utilities as a demand side management measure since common area amenities are billed under domestic tariff category.

ACKNOWLEDGEMENT

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Parts this paper along with complete results of the analyses, and in-depth description of the methodology, findings and recommendations will be a part of a soon-to-be published working paper (January 2020).

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OPTIMIZED BUILDING CONTROLS AND GRID INTEGRATION

Paul Ehrlich, PE[1]

[1]*President*
Building Intelligence Group LLC
Portland, Oregon, USA
Paul@Buildingintelligencegroup.com

ABSTRACT

Commercial building controls can have a dramatic impact in achieving energy efficiency. Properly designed and implemented integrated controls provide a tool that helps deliver efficiency and supports operation of the building. These same systems can be used to provide building to grid integration, allowing the building to provide grid services along with support for fault detection and analytics.

As an industry though, we often fail to deliver control systems that meet these goals. This paper covers the design of integrated controls, key efficiency strategies, and programs under way to improve the control design and delivery process. Case studies on both improved efficiency as well as building to grid integration is included.

Keywords—Building controls, efficiency, integration, building to grid, open protocols, optimization

INTRODUCTION

Commercial buildings rely on control systems for safe and efficient operation. Initially, controls were developed primarily for controlling temperature. In fact, the earliest controllers were called "regulators" since they would regulate the temperature, typically with some form of a mechanical control. In the US and Europe, these systems evolved over the years from being primarily mechanical to using sophisticated electronic or pneumatic logic for both control and actuation. As computer technology emerged from 1970 – 1980, building controls evolved into the use of direct digital control (DDC). This allowed for control systems that were not only more accurate and repeatable, but with the added benefit of being able to utilize communications for easy monitoring of system operation remotely. By the 1990s, the use of building automation systems (BAS) became cost effective and common for new buildings. However, these new systems were frustrating for owners since they were highly proprietary, and it was often difficult and expensive to get service and support for an existing system and even more expensive to expand it. This spurred the industry wide development of open communications protocols including BACnet (BACnet International, 2019) from ASHRAE, Lon Works (LonMark International, 2019), and Modbus (Modbus International, 2019). Today, the majority of new systems utilize open protocols, while existing buildings are a mix of open and proprietary systems.

Note that the author works as a consulting engineer and researcher in the field of commercial controls and is based in North America. As a result, most of his project experience is on buildings in North America, however he has been involved in projects in India as well as Europe and Asia. The control products being used in North America are from large global suppliers including Honeywell International, Schneider Electric, Johnson Controls and United Technologies. These are the same suppliers that are also involved in markets including India, Europe and Asia. There are however a few key differences between what may be found in North America and in other markets. One is that the vast majority of large commercial buildings in North America were constructed prior to the year 2000 and as a result, often have either obsolete control systems or are on their second or third generation of controls. Evolving markets often have the benefit of newer buildings that may have been designed and constructed using more recent technology. There is also a difference in system types found in the US. US HVAC systems are largely air based, while systems found in other markets may tend to be more refrigerant (i.e. VRF, mini splits) based or water based (fan coils). The basics of controls optimization and grid integration as described in this paper, however, readily apply to systems found in all markets globally. Unfortunately, the challenges found with the inability to get systems to operate at their full efficiency also exist globally.

Building controls can be an effective tool to operate buildings for optimum efficiency. They do this through the use of sensors, actuators and control logic that is used to condition spaces only when required, and to deliver the required level of heating or cooling to maintain occupant comfort and safety. A properly "optimized" control system can operate a building at peak efficiency. However, a system that is poorly designed, not correctly installed, or improperly operated can result in significant energy waste. Studies and energy audits regularly show buildings using from 10% to 50% more energy than needed often due to poor control system performance. (N. Fernandez, 2017). Figure 1 illustrates the challenge found in many buildings. The control system is designed for an initial level of efficiency, which due to various reasons is operating at a lower level of efficiency (as measured by the energy use index or EUI). The system can be recommissioned to bring it back to the original design; however, they tend to drift back to run at reduced efficiency. Proper optimized control design coupled with tools improve performance provides the ability to improve performance over time.

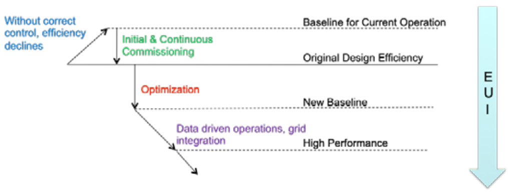

Figure 1: Building Efficiency over Time

Building control systems are also able to receive signals based on the needs of the electrical grid. The control system can then take a pre-defined control action. For example, on a hot day there may be more demand for electricity than is available. The grid operator can respond to this by dispatching additional generating or storage capacity (if available), or by restricting usage through rolling blackouts. An alternative is to send a signal to buildings that in turn has them minimize usage for a period of time. This is often called "Shedding" or "Demand Response" control. Additional grid services that can be provided by buildings include the ability to "shift" their demand, as well as to "modulate" (or shimmy) loads. See figure 2 and (Piette, 2017). Shifting demand is an effective strategy for management of a grid that has a high percentage of intermittent renewable generating resources. In a shifting strategy the building shifts its energy use to accommodate the grid. For example, at noon on a sunny day the electrical grid may have excess capacity from Photo Voltaic (PV) generation. A signal is sent to the building requesting a shift. The building control system would then be able to trigger additional loads that could charge a thermal storage plant, pre-cool the building, or charge an on-site battery. Modulating or shimmy is the least mature building to grid strategy. In this strategy the grid is requesting fast changes so that the voltage and frequency is maintained. Most building control systems are not designed for fast action, and as a result most modulating strategies rely on other systems such as adjustments to solar PV inverters. The use of building to grid control is an important strategy for managing an electrical grid that has a high percentage of intermittent renewable resources, allowing for buildings to flex their usage to balance the available supply. Note that most building to grid control for commercial buildings today is limited to demand response (shed) and is often a fairly manual process initiated by a building operator at the request of the utility. The use of more automated and sophisticated building to grid strategies is largely a research topic and is not yet being broadly deployed.

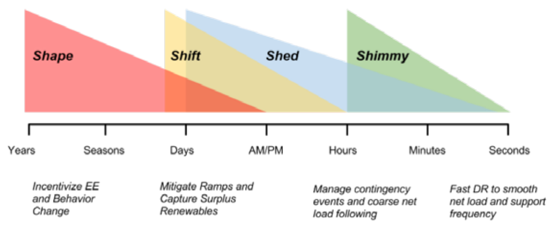

Figure 2: Building to Grid Services (courtesy of DRCC)

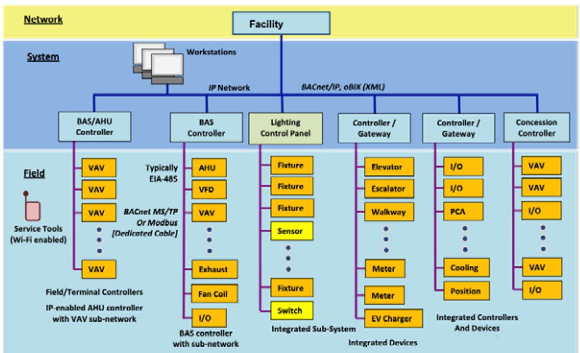

Figure 3: Integrated Commercial Building Control Architecture

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HVAC Control

In most buildings, Heating Ventilating and Air Conditioning (HVAC) is the largest consumer of energy in the building. There are many ways to reduce HVAC energy use including the use of more efficient building envelope design and construction, improved equipment efficiency, and proper operations and maintenance. The use of controls also has a large impact on energy used for HVAC. The key elements to an optimized HVAC control design include:

- Only run when needed: Equipment that is turned off is generally at its most efficient point of operation! Systems should be operated as required to maintain occupant comfort and safety. However, there is no reason to run a system for an area that is not occupied. The use of schedules, occupancy sensing, and algorithms such as optimal start allow for control systems to only operate when required.
- Optimization: The basics of optimization are based on the following:
    - Free Cooling: Use cool and dry outdoor air when possible in place of mechanically cooling.
    - No Simultaneous Heat / Cool: Avoid cooling down air then heating it again as is done, for example, in a reheat system.
    - Select Maximum Efficiency: Operate the most efficient combination of equipment to meet the load of the building. For example, if there are multiple chillers, the most efficient combination of machines would be selected to run to meet the load.
    - Deliver at Minimum Energy: Provide comfort by moving the least possible amount of air and water, at the lowest possible pressure. By reducing both flow (kinetic energy) and pressure (potential energy), comfort can be provided with minimal energy. An example of this is resetting the static pressure in a pumping system based on the valve positions so that the most extreme valve is always 100% open.
    - Manage Ventilation: Deliver the required level of fresh air to each zone based on actual occupancy, not the design assumptions.

Lighting Control

Since lighting is typically the number two energy user in a commercial building, providing better control is a good strategy to reducing energy use. There are several control strategies typically used for lighting control. These include:

- Scheduling: Lights that serve common areas such as lobbies, corridors, and open office areas can be scheduled so that they are shut off when the areas are not in use. Exterior lights can also be scheduled or may be controlled based on daylight levels (with a photocell).
- Occupancy Based Control: For areas with intermittent occupancy such as classrooms, conference rooms, and private offices, the best option is to have lighting controlled based on occupancy sensing. There are two strategies that are often used. One is to use a motion sensor to turn the lights on when activity is sensed. The other strategy is called vacancy control, and it requires that the lights be turned on manually using a switch, and that the motion sensor will turn the lights off when no activity has been sensed for a time interval.
- Daylight Harvesting: In many zones, there may be windows and skylights that provide daylight. In these zones lighting sensors can be used to measure the daylight level, and lights can then be dimmed or turned off to hold a constant level of lighting in the zone.

Lighting control systems have evolved from being simple relay-based switching of large banks of lights to being deployed directly as part of the fixture. The latest lighting control solutions embed a small sensor in each fixture that is able to sense daylight levels and occupancy. They can communicate wirelessly so that the fixtures can share both data and control. For example, a group of fixtures in a conference room might be programmed to turn on and off together, and to adjust their output based on the level of light coming through the windows. They also can be connected to local control (which replaces the traditional light switch) and be integrated into a building control system.

Since lighting control and HVAC both require information about occupancy, the sensors installed as part of the lighting control system are often used to set the occupancy mode of the HVAC system. This type of integration provides for improved efficiency without having to purchase the sensor for both systems.

METHODOLOGY

The goal of utilizing building controls is to measure, monitor, and control, providing data for more efficient and effective operation of the facility. But unfortunately, building controls often do not operate as well as would be desired. There are many reasons for this. Part of it begins with system designers who are more skilled on designing mechanical systems than on controls. It then passes to the contractor who is under pressure to finish the project on schedule and budget, and finally to operators who are often undertrained to utilize these systems. There are numerous programs under way in the industry to help to overcome these issues, improving the quality and performance of these systems.

- Optimization: Properly applied and programmed, building controls can dramatically reduce the energy use of a commercial building. This is done through a series of strategies that start with monitoring and maintaining occupant comfort and Indoor Environmental Quality (IEQ), then moving the minimum amount of air and water to deliver those conditions. Unfortunately, these optimized conditions are often not achieved, due to issues related to the design, poor programming or overrides by the building operator. There are a series of new efforts underway to try to overcome these issues. This includes language in new US energy codes that require optimization, efforts by organization such as ASHRAE to document best practices (ASHRAE Guideline 36 (Guideline 36, 2019)), and work being conducted by the US Department of Energy National Laboratories to create process improvements for the design and delivery of control system sequences called Open Building Control (OpenBuildingControl, 2019). Optimization can be applied both on new buildings as well as retrofitted to existing systems.

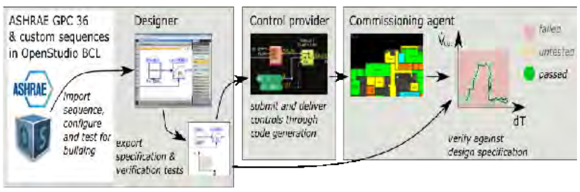

Figure 4: Open Building Control Digital Process Flow

- Semantic Tagging: Control systems are typically designed and installed with a graphical user interface. This interface (typically in a web browser) provides information in a way that allows the user to see the information in semantic context. For example, a floorplan may show the current temperature and setpoint for each room, helping the operator grasp the data and its relationship to the building. When the data for the building is needed for another purpose though, such as analytics or fault detection, the semantic information is hard to determine. The data object for a room's temperature now just says "Room 101" with no context as to what the value is, the room location, or what air handler serves that room. Semantic tagging can provide that additional context, allowing better use of control system data. There are a series of efforts underway to create semantic tagging standards. This includes work from "Project Haystack" (Project Haystack, 2019) and "Brick" (Brick Schema, 2019). Most recently, ASHRAE has partnered with Haystack and Brick to develop an ANSI standard for semantic tagging (ASHRAE Proposed Standard 223, 2018).

- Energy Management Information System (EMIS): Being able to use building control data for applications other than control has the ability to assist operators in making better decisions and improving the operation of the facility. EMIS tools use control system data to provide added processing of data into knowledge. There are many different types of EMIS tools including those that are focused on Energy Information (EIS), Fault Detection and Diagnostics (FDD), and evolving tools that analyze problems and attempt to modify the control logic to resolve the problem called Automated Systems Optimization (ASO). The US Department of Energy is providing a campaign to help educate and promote the use of smart energy analytics (US DOE Smart Energy Analytics, 2019).

- Building to Grid: Programs to allow buildings to participate in demand response programs have been in place for many years. New research is underway to develop models, standards, and programs that will allow buildings to participate in a variety of grid services. This has value in managing the electrical grid for improved resilience and reliability, especially when generating resources are intermittent. The US Department of Energy has a new program focused on efficiency and grid services for buildings called Grid Interactive Efficient Buildings (US DOE, 2019).

- Cyber Security: While building controls are not as critical as control of the electrical grid, they still are responsible for maintaining safety and comfort in critical facilities such as schools, hospitals, and office buildings. Control systems are often network enabled and connected to the

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Internet which makes them accessible to attackers. There is significant effort ongoing in industry to address the issue of cyber security and to both implement best practices to protect current systems and to develop new, more secure technology.

DISCUSSION AND RESULTS ANALYSIS

The building controls industry is highly consolidated and relatively slow to change and adopt new technologies, however, there are a number of areas of significant innovation that are currently underway. The use of these new technologies is anticipated to have a positive impact on the performance of controls for improved efficiency.

- Model Predictive Control / Artificial Intelligence (MPC / AI): There is significant research and development under way to utilize new technology to improve how well controls work. These new technologies include the use of machine learning and artificial intelligence. For controls, one of the most significant changes is the use of Model Predictive Control (MPC). MPC is a control process based on a mathematical model that can be enhanced over time through observed responses, a process called machine learning. The use of MPC can provide more accurate and efficient control that can balance complex needs such as comfort and efficiency. Currently, these new methods are being used in controls that are integrated into equipment, but new research is underway to include them in applied systems as well.
- Integration: System integration is often considered to be too complicated and expensive to pursue, but the broad use of open standards and solutions such as semantic tagging are driving down the cost and complexity of integrated systems. The driver for expanding systems integration will be energy, but also for improvements in operational efficiency and comfort.
- Comfort management: The building control industry has long been focused on the improvement of the efficiency of commercial buildings. Building owners are now shifting their focus to improving the comfort, and ultimately, the productivity of the building's occupants. Comfort is a complicated topic and is impacted by temperature, humidity, light levels, ventilation, noise, and odors. The perception of comfort also is inconsistent, varying from occupant to occupant. There is more and more interest in the topic of comfort and ventilation, and ideally, a desire to better measure comfort parameters through enhanced sensing and also to deliver comfort on an individual basis.
- Optimized operations / data driven: Building controls have always been focused on safe and efficient operation of equipment along with providing information to the building operator. As the operation of buildings becomes more demanding and more experienced building engineers are retiring and exiting the workforce, there is a need for control systems to provide added support for building operations. One way that this can be done is with new applications which take building control system data and convert it into actionable information. This information can then be used to take actions or be transferred into work order processing systems so that repairs can be scheduled.
- Role of facility management (FM) and Information Technology (IT): There are some similarities in the work required to manage facilities and information technology. Building controls have an even greater synergy since they are computer based and communicate on data networks. Many owners are looking at opportunities to bring these support areas together.

EFFICIENCY CASE STUDY

Davidson College is a small, highly regarded liberal arts college, located just north of Charlotte in Davidson, North Carolina, US. Their sports arena consists of three large sports areas: basketball arena, tennis center and aquatic center. In addition, there are work out rooms, a wrestling room, dance studio, equipment rooms, locker rooms and office space. The basketball arena is used for a wide variety of events including men and women's basketball, wrestling, volleyball and intramural sports. The occupancy of this space can range from a few occupants to as many as 4,800 people during a well-attended basketball game.

Figure 5: Davidson College Belk Arena

The building is approximately 25 years old, and many of the building systems were no longer operating at peak efficiency. Mechanical systems include constant volume, variable volume, and multi-zone air handlers. While the building is only occupied for a part of the day, the mechanical systems were operated continually. All lighting for the building was manually controlled. Central plants for steam and chilled water serve the building. The sports arena, as well as the entire college campus, is connected to an Automated Logic WebCTRL BAS, however the majority of the building controls was the pneumatic system installed in the 1980s and was no longer operating properly.

The sports complex uses campus-provided utilities including electricity, chilled water, and steam. While the owner had installed sub-meters in the building for all of these utilities, the data had not been recorded or stored. This made the calculation of an accurate energy use index for the facility impossible. In order to learn more about the facility, a detailed engineering study was conducted. This included an evaluation of the original design, testing of all systems, and deployment of over 50 data loggers to record temperatures, humidity levels, current draw, and other parameters over an interval of several weeks. The results of this study showed the potential for significant energy conservation measures, which had the potential for both reduced consumption as well as peak demand reduction. The program approved by the owner included:

- Controls Upgrade: Replaced all existing pneumatic controls with a new BAS, providing the owner with the ability to readily manage the building. This also was required in order to deploy the strategies described below.
- Air handler conversions: The original air handling units in the building were designed with fans that operated at a constant speed. These units were retrofitted with variable frequency drives, which allowed for the fan speed to be controlled. Reducing fan speed provided the ability to significantly reduce building peak energy usage. For example, two constant volume fans that together used 16 kW of power originally served the basketball arena and were used for normal operation. The arena also had four larger units, which were used during large events. Abandoning the small units and retrofitting the large units with variable frequency drives reduced fan power to a total of 0.8 kW and still provided the same amount of airflow to the arena.
- Controls optimization: A series of optimization algorithms were deployed. These included resetting pressures and temperatures, scheduling of equipment based on actual occupancy, and controlling unit operation based on building occupancy.
- Lighting control: Occupancy sensors were added for lighting control. A subsequent project also included upgrades to lights in the pool area.
- Project Results: The retrofit project achieved a reduction of peak consumption by over 20 percent (47 kW). Annual energy use (steam, chilled water and electricity) was reduced by over 40%.

An additional case study from the author is available at (Ehrlich, Paul, 2014).

BUILDING TO GRID CASE STUDY

Duke Realty's Towers of Kenwood in Cincinnati Ohio, US consists of two office towers, each about 200,000 square feet, totaling 402,000 gross square feet. The two towers are connected by an atrium. Each of the seven-floor towers provides multi-tenant Class A office space. An in-house team manages the facility. Most of the tenants occupy the building during regular office hours, although a few tenants use the building 24 hours a day.

Figure 6: Towers of Kenwood

The East tower has over 250 water source heat pumps to provide heating and cooling for the building

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occupants. Each office area has a series of small heat pumps, each with a networked thermostat. This allows each tenant to control the temperature of his or her space. Other mechanical systems in the building include make-up air ventilation units, cooling towers, pumps, and boilers.

One of the central goals of the project was to integrate the building automation system with the utility to support automated demand response capability. Some of the benefits of integration include:

- Real-time information provided to the owner from the main electrical meter about consumption and demand.
- Utility receives additional information about consumption and demand at both the main and sub-meter level for selected areas of the building.
- Demand response signaling – the utility can send the building a signal to reduce demand, and the building can react automatically.

Energy Use and Demand

In 2010, an analysis was completed to benchmark the energy usage of the Towers of Kenwood building with data from the US EIA Commercial Building Energy Consumption Survey 2003 for office space. The analysis found that electrical consumption was about 40 percent higher than the benchmark. Although natural gas consumption was below the average, the total energy cost and usage was more than 25% above the benchmark.

To increase energy efficiency, HVAC equipment scheduling, and thermal loop optimization was implemented. In addition, to reduce peak demand, demand response capability was put in place.

From an energy efficiency perspective, the changes were anticipated to produce a 15% reduction in energy use. At the time of this update, with approximately one year of operation since the retrofits were completed, the building has consistently demonstrated a 16% reduction in energy use relative to the baseline performance established prior to the retrofits. Demand response capability established as part of the retrofit goes beyond mere efficiency to allow the utility to request load reduction to which the building responds automatically in real-time.

Building to Grid

Building to grid connection capability was demonstrated in testing over a period of one week, from June 20 to June 24, 2011 for the East office tower. The five days of experimentation tested four different response levels of increasing severity and a business-as-usual condition. To initiate the testing, the utility sent a demand response signal each day to which the building responded automatically using pre-programmed logic. The building's demand was monitored to quantify the building's response.

Upon the utility's signal to initiate a demand response event, the BAS receives a numerical signal and automatically responds using a pre-defined fully automated algorithm. Table 3-1 shows the four demand response levels and associated behaviors. Based on the level received by the BAS, it in turn communicated the appropriate commands to controllers throughout the building, adjusting temperature set-points and/or controlling water heaters and coolers. The duration of the test events ranged from two to six hours. Average demand reductions ranged from 57 kW to 149 kW, in direct relationship with demand response levels. Feedback from tenants, forewarned of the testing, was limited to the fourth day of testing when the property manager received a complaint that space conditions were uncomfortable.

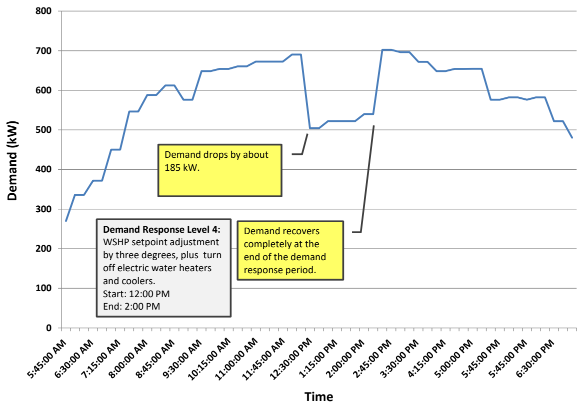

Figure 7: Load profile for Day 4 testing (Thursday)

Technologies Applied to Implement Automated Demand Response

In order to automate demand response, basic infrastructure was installed including communicating meters and an integration gateway. Mechanisms of control and infrastructure for demand response included wireless communicating thermostats, discrete control points and sub-meters.

Water source heat pumps: Wireless thermostats provided the means of control for the water source heat pumps. The BAS communicates setpoint changes to the thermostats based on the demand response signal. The Zigbee wireless thermostats were selected because the installation was greatly simplified relative to using conventional wired communicating thermostats. Each wireless thermostat replaced an existing stand-alone thermostat. Therefore, power wiring already was in place for each thermostat, and communications wiring was not necessary.

Water heaters and coolers: To control the domestic electric water heaters and water coolers based on demand response signals from the utility, a digital output from the BAS in combination with a relay control were employed for each load.

Sub-meters: Beyond this basic infrastructure, sub-meters were installed to monitor various loads in the central plant and on two representative floors by end use. Specifically, the loads included:

- In the penthouse central thermal plant:
    - Loop pumps
    - Cooling tower pumps
    - Cooling tower fans (and VFDs)
- On floors three and four, subpanel loads by end use:
    - HVAC
    - Lighting
    - Plug load

Sub-meters were integrated with the BAS using Modbus, making sub-meter data available to the building operators and managers as well as to the utility.

Demand response testing at Towers of Kenwood implemented and successfully demonstrated the following:

- The use of wireless mesh networking technology to economically connect and enable control of previously independent HVAC equipment.
- The application of micro-load control for demand response, specifically for domestic water heaters and water coolers.
- The ability to shed substantial load on demand in an office-building environment without generally adversely affecting occupant comfort.
- The integration of utility systems with building automation for two-way communication, and the use of building automation and utility information systems to monitor demand response in real time, and to maintain historical data.
- Average demand reductions ranged from 57 kW up to 149 kW, or from 8% to 21% of peak demand, for durations ranging from two to six hours.

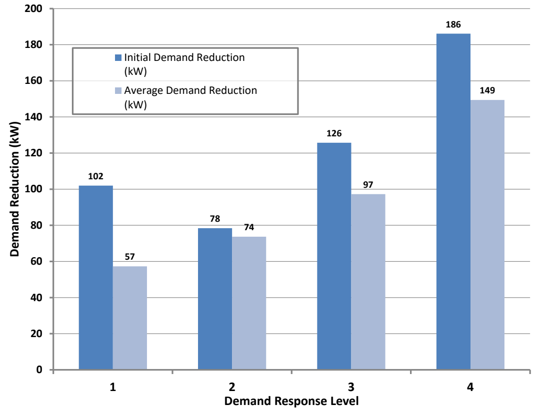

Figure 8: Demand response testing summary

CONCLUSION

Controls, when properly applied can be an important tool to improve energy efficiency and also to support building to grid integration. However, these systems often underperform, largely due to the process challenges in design, installation and operation. Today control products are relatively economical and readily available from global suppliers. There are a number of efforts underway to improve both the process and the technology used in building controls to improve their performance. However, these changes are slow to be adopted and in the meantime building performance suffers. There are several potential solutions to this challenge. One path is to shift building controls to the use of new technologies as identified in this paper. For example, the use of MPC and AI could result in more intelligent systems that would be able to be optimized and require less skill and involvement from designers and installers. The other path is to continue to improve the skill set and processes used for controls systems design, delivery and operation. The new of programs to document best practices (such as ASHRAE Guideline 36) and new digital tools all show great potential. Ultimately the solutions need to build from both of these approaches.

Building to grid integration is still an area that is largely nascent. Programs for shifting demand have been in place for decades but allowing buildings to provide more sophisticated services is slow to evolve. There is great potential in delivering building to grid integration, but work is needed to better understand building physics, occupant comfort, and the economics of grid services to make these programs practical and widely deployed.

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THE INTERSECTION BETWEEN THE DIGITAL REVOLUTION AND THE NEED TO DEVELOP HUMAN CAPITAL IN THE FACILITY MANAGEMENT INDUSTRY

Emilie Bolduc[1], Rebecca Hughes[2]

York Energy Manager
ork Power Authority
y, New York, U.S.A.
.Bolduc@nypa.gov

York Energy Manager
ork Power Authority
y, New York, U.S.A
ca.Hughes@nypa.gov

Any opinions expressed in this paper are those of the author(s) and not those of the New York Power Authority.

ABSTRACT

Big data, machine learning, and artificial intelligence are dramatically changing facility management and its workforce. While some experts argue the digital revolution will supplant some of the facility management workforce, the objective of this paper is to provide evidence that technology and digitization will enhance this workforce and allow them to more effectively and efficiently operate facilities. This paper will introduce the concepts of "Fast and Slow Thinking" and provide examples of how technology and digitization are bringing "Slow Thinking" to the "Fast Thinking" human workforce to better manage and operate buildings. It will also provide examples of concerted efforts to train energy managers on new technologies and data science, helping to mitigate labor market challenges and reinvigorate trade workers.

Keywords—big data, facility management, labor market conditions, digital energy management, building automation systems, energy management information systems

INTRODUCTION

The application of big data and data analytics to drive energy efficiency in buildings has gained prominence in recent years. Data from building automation systems, main load metering, equipment-level submetering, and sensing technologies are able to identify how to improve building energy performance and drive non-energy benefits including improved operational efficiency, occupant comfort, and productivity.

But at the frontier of the energy management revolution is a dynamic tension between cutting edge trends like artificial intelligence and machine-to-machine (M2M) learning and real world labor market conditions like attrition due to retirement and a dwindling talent pipeline.

On one end of the spectrum, we have technological advances that are leveraging the power of big data analytics to identify opportunities in real-time to drive down energy costs and consumption while mitigating peak demand. On the other end, we are facing significant labor market changes, including skills shortages in the trades, that threaten to undermine clean energy market growth.

The purpose of this paper is to investigate how facility management can continue to advance digital solutions while mitigating labor market challenges.

METHODOLOGY

1. Look at trends and labor statistics for the facility management industry in the US and globally.
2. Apply behavioral economic principle to data/technology trend and facility management workforce.
3. Attempt to answer the question: Will the biggest factors impacting facility management in the next ten years—data and technology—replace or enhance our workforce?

4. Illustrate ways in which data and technology with proper training can enhance facility management workforce.
5. Identify what is needed to fill the training gap.

DISCUSSION AND RESULT ANALYSIS

Facility Management Industry Trends

With humans spending approximately 90 percent of their time indoors, it explains why facility management is such a significant market.[1] The global facility management services market was approximately $1.314 trillion in 2018 and is expected to grow to $2.127 trillion by 2027.[2]

One of main drivers for this growth is the rising corporate social responsibility concerns to decrease ecological footprint.[3] A growing trend of building management or companies outsourcing their facilities management services is also driving this market growth.[4] This move is not to reduce costs, but rather to give in-house facilities teams the opportunity to focus more on “strategic initiatives and enhancing the user experience.”[5] User experience means focusing on occupancy comfort, and provinding a more personalized experience to occupants, which includes the technology, services and amenitites that help occupants be more productive.[6] One significant trend driving the facility management market growth is the adoption of the Internet of Things (IoT) and connected devices for building automation.[7]

The facility management workforce is having to adjust to these trends and changes. At the same time, the facility management workforce is experiencing its own changes. According to the IWFM, Millenials/Gen Y will account for nearly 48 percent of the labor force (with Gen X making up more than a quarter) by 2025.[8] Furthermore, much of the existing facility management workforce will be retiring in the next ten years. In 2008 survey comprised of 1,164 facility management personnel across the US, the findings revealed that median age of facility professionals who responded to the survey were 50 years old, with seven percent of the respondents having worked in the industry less than four years in comparison to 54 percent who have worked for twenty or more years.[9] This industry is poised for a major shift as these older, more experienced employees retire out of the industry.

Additionaly, employment in facility management is growing.[10]

Job Title	Employment (2000)	Employment (2016)	Annual growth
Heating, Air Conditioning, and Refrigeration			
Mechanics and Installers" (49-9021)	197,930	294,730	2.5 percent
Construction and Building Inspectors" (47-4011)	68,690	94,960	2 percent
Security and Fire System Installers (49-2098)	38,810	67,700	3.5 percent

Source: Bureau of Labor Statistics

Figure 1: Job Growth in Selected Building Management Categories, 2000-2016

It is important to understand that there are varying roles and positions within facility management. The International Facility Management Association (IFMA), groups the facility management labor force into three categories:[11]

Professional – Building/Facility management staff typically salaried expemt (not eligible for overtime) employees trained as specialists or managers.

Skilled trades – Trained crafts or trades staff such as electricians, plumbers, carpenters, painters, HVAC, controls, furniture tech or stationery engineer.

Non-skilled workers – Building/Facility management workers who are not necessarily trained or skilled perfomring duties such as custodial, grounds keeping, food service or moving.

The facility management trends mentioned above will affect all three categoris of workers in facility management, with the adoption of IoT and connected devices to be the most disruptive. But disruption is not always negative. Facility management technology and digitization has the ability to enhance facility management staff in decision making, make their jobs more efficient, and allow them to focus on the increasing need for occupant comfort and user experience.

[1] EPA, 2019.
[2] Zion Market Research, 2019.
[3] Ibid.
[4] CBRE, 2018.
[5] Ibid.
[6] Dukes, 2019.
[7] Reuters, 2019.
[8] Global FM, 2018, p.12.
[9] Lorenz, 2008.
[10] MACH Energy, 2018, p. 4
[11] IFMA, 2010, p. 17

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Fast and Slow Thinking

In Thinking, Fast and Slow, Daniel Kahneman summarizes two modes of thinking this way:[12]

> **System 1 (or Fast Thinking).** Fast Thinking operates automatically and quickly, with little or no effort and no sense of voluntary control. Fast Thinking seeks a coherent story above all else, and often leads us to jump to conclusions. While Fast Thinking is generally very accurate, there are situations where it can make errors of bias. Fast Thinking sometimes answers easier questions than it was asked, and it has little knowledge of logic and statistics. One of the biggest problems with Fast Thinking is that it seeks to quickly create a coherent, plausible story—an explanation for what is happening—by relying on associations and memories, pattern-matching, and assumptions. And Fast Thinking will default to that plausible, convenient story—even if that story is based on incorrect information.
>
> **System 2 (or Slow Thinking).** Slow Thinking is effortful mental activities, including complex computations. Slow Thinking is demanding, strenuous and we tend to use it as rarely as possible. It is activated on reaction when something surprising happens in the world, or on purpose when we need it. Slow Thinking can, among other things, solve new problems, follow multi-step instructions and apply learned rules.

Most humans identify with Slow Thinking. We consider ourselves rational, analytical human beings. Therefore, we must spend most of our time engaged in Slow Thinking. Actually, we spend almost most of our daily lives engaged in Fast Thinking, because it is easy, effortless and slow thinking is difficult.

Fast and Slow Thinking applies to facility management. Facility personnel are quick to rely on their past experiences and assumptions to diagnose issues with building equipment. As facility management personnel are asked to manage more buildings and equipment, they will not be able to rely on these past experiences as often. And if one is to follow Kahnamen's argument, their assumptions informed by past experiences are the product of Fast Thinking and may not be accurate.

Kahneman saw "a very useful role for an "intelligent" computer system to be a kind of over-the-shoulder critic to assist human decision making – bringing the slow-thinking perspective, with its careful parsing of evidence – to supplement and enrich fast thinking by humans."[13] It is the role of big data, data science, and artificial intelligence to bring the power of Slow Thinking to the human-default Fast Thinking. A"clever helper," Lohr calls it, in human decision making.[14] Big data and technology are useless without humans to direct its purpose and to utilize it to drive action.

Digitization and Technology in Facility Management for Building Systems

The facility management sector has been installing and utilizing sensors to monitor equipment and systems withing buildings and a facility as a whole, but some argue there is an imbalance between data capturing and data analytics – many are not using the data extensively for evaluation and real-time analysis.[15] While the adoption may be slower than in other industries, the digitization (i.e. IoT and big data analytics) of the architecture, engineering and construction industry, including facility managerment, is taking place because it is resulting in the reduction of asset maintenance costs; the creation of better tailored or customised services to individuals and groups; more accurate forecasting; risk mitigation; resource levelling and space optimisation; performance measurement & verification; and informed investment decisions, and, on a greater scale, "smarter" cities with predictive solutions.[16]

Specific to the facility management industry, the main drivers for the increased adoption of new technology and digitization are an improved data-driven decision-making process (i.e. more effective use of heating and cooling systems in buildings), more sustainable design solutions that can help reduce energy consumption, prediction of maintenance dates or identification of faults and diagnosis of problems with the equipment and systems within facilities, and the consequences of these decisions on nearby facilities.[17] Giving organizations a competitive advantage is also another important driver for using big data.[18] All of

[12] Kahneman, 2011.
[13] Lohr, 2015, p.67-68.
[14] Ibid.
[15] Granberg, He, 2018.
[16] Ahmed, V., Tezel, A., Aziz, Z. and Sibley, M. (2017), p. 6.
[17] Ibid, p. 14.
[18] Ibid, p. 14.

these will ony be realised if the facilities and organisations owning the buildings are equipped with systems and platforms that have the capacity and capability to capture large volumes of data, with a level of intelligence that can react to this data input in real time, as well as developing the right IT skills within organisations that will deal with the data.[19]

The biggest challenges slowing down the adoption of big data and technology in the facility management industry are obtaining, structuring and managing the data, the need for change in the culture and attitude towards sharing project data, and the need to understand the business value.[20] In one study, when asked about the biggest operational challenges that face the utilisation of big data analytics in the facility management industry, 42 percent of the participants felt that finding the right talent that is capable of working with new the technology and interpreting the AEC processes is the most significant barrier.[21]

Workforce Training – How to mitigate the workforce issues

As new technologies and concepts of energy management are introduced to the field of facility management, worker skills must be advanced commensurately. This includes new and emerging workers as well as incumbent workers who require re-skilling or skill enhancement.

Accoring to the 2010 New York State Green Jobs Study[22], employers of building services staff favor on-the-job training and in-house resources to train their workforce over traditional classroom training through labor unions or post-secondary education institutions. On-the-job training and internships can serve multiple purposes: they can be an efficient way to impart new skills for existing workers who are learning while performing job-related tasks and they can serve as valuable tools for the recuitment of entry-level workers who are entering the workforce or transitioning from another role.

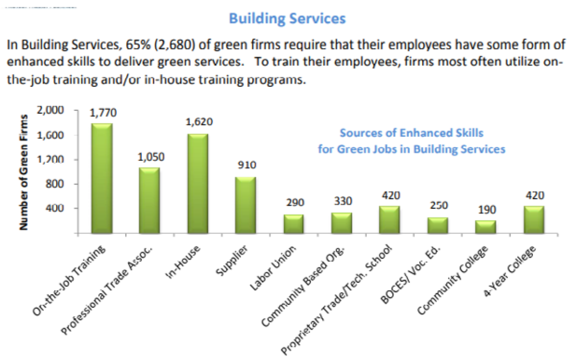

Figure 2: Sources of Enhanced Skills for Green Jobs in Building Services

Public-private partnerships supporting skill enhancement

On-the-job training is akin to apprenticeship training which allows the participant to "earn while they learn" under the tutilage of a more senior worker. Under this model, select staff attend a training and are then responsible for transferring knowledge to their colleagues in the field.The New York State Energy Research and Development Authority (NYSERDA) issued Program Opportunity Notice 3715[23], Building Operations and Miantenace Worforce Development and Training Program, provides incentives to employers and building owners to impliment classroom and on-the-job training programs that build upon employees' technical skills and reduce facility energy use. NYSERDA, under Program Opportunity Notice 3982[24], provides incetives to eligible applicatis who provide on-the-job training to new workers or to incumbent workers being advanced in new clean energy roles including facility management. Both program recognize the need for jobsite-based training opportunities that help to bridge the gaps between labor supply and demand for skilled workers.

Industry-recognized training resources

In addition to jobsite training, there are also reputable third party training programs that help to advance the skills of facilities management staff in leveraging data to better operate and manage energy-consuming equipment.

- Pacific Northwest National Laboratory developed Building Re-tuning ™[25] to train facilites staff to detect energy savings

[19] Ibid, p. 14.
[20] Ibid, p. 10.
[21] Ibid, p. 10.
[22] NYS Department of Labor, 2010.
[23] NYSERDA, 2019.
[24] NYSERDA, 2019.
[25] PNNL, 2019.

opportunities and to impliment efficiency measures.

- The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) offers a series of courses on energy management best practices[26].
- The City University of New York Building Performance Lab[27] (CUNY BPL) delivers courses on the interpratation of energy trend data and change point regression modeling to facilities and building operations staff across New York City.
- The Association of Energy Engineers (AEE), a membership organization, offers a range of energy and facility management certification programs[28].

Training opportunities

- Need to embed digital/IT into existing post-secondary degree and continuing education programs aimed at facility managers and technicians
- Need employers to see the value in investing in skill development and enhancement
- Need to update registered apprenticeship programs (US DOL)

CONCLUSION

The facility management sector has and will continue to install and utilize sensors to monitor equipment and systems withing buildings and a facility as a whole. Finding the right talent that is capable of working with new the technology and interpreting the facility data is the most significant barrier. As new technologies and concepts of energy management are introduced to the field of facility management, worker skills must be advanced commensurately. In addition to jobsite training, there are also reputable third party training programs that help to advance the skills of facilities management staff in leveraging data to better operate and manage energy-consuming equipment.

Facility management can continue to advance digital solutions while mitigating labor market challenges. Facility management technology and digitization has the ability to enhance facility management staff in decision making, make their jobs more efficient, and allow them to focus on the increasing need for occupant comfort and user experience.

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CONTINUOUS CONDENSER CIRCUIT OPTIMIZATION IN WATER-COOLED CHILLER PLANTS

Ananthapadmanabhan G S[1], Divya Kritika[2]

[1]*Analytics and Automation*
Smart Joules Private Ltd
New Delhi, India
ananthapadmanabhan@smartjoules.in

[2]*Analytics and Automation*
Smart Joules Private Ltd
New Delhi, India
divya@smartjoules.in

ABSTRACT

Cooling towers and condenser pumps together account for 20% of the energy consumption of water-cooled chiller plants, and substantially impact chiller energy consumption through condenser inlet temperature. Traditionally, operators run these equipment's either at full blast to minimize condenser inlet temperature, or without any specific logic whatsoever. The consequence is wasted energy consumption and carbon emissions, and excessive expenditure on air conditioning.

Can data lift the veil that shrouds efficient condenser circuit operations and show us a better way?

Smart Joules has been experimenting with various combinations of cooling tower fan frequencies and condenser line water flows across hospitals in different climatic conditions in a quest to discover operational strategies that minimize overall chiller plant energy consumption. This paper presents a case study of such experiments executed in different hospitals in India.

Our findings reveal that the sweet spot combination of cooling tower speed and condenser water flow that minimizes overall chiller plant efficiency is dynamic and dependent upon cooling tower approach. In this case, cooling tower frequency was found to be the primary energy saving lever while the cooling tower approach was less than 10°F, and the condenser line flow became the primary accelerator otherwise.

Based on our experimental observations, this paper proposes generic logics for operations of condenser circuits in centralized cooling systems that could have wide-ranging implications on unlocking energy efficiency across industries.

Keywords— *Chiller, Condenser Pump, Cooling Tower, Approach, Energy Effciency.*

INTRODUCTION

In centralized air conditioning plants with water cooled chillers, the condenser circuit comprising condenser water pumps and cooling towers consumes about 20% of the energy of the total plant room and plays a critical role in maintaining optimum chiller as well as the plant room performance. The most common approach observed in practice across different water cooled chiller plants in India is to run the condenser pumps and cooling towers at full capacity with the aim of achieving the minimum possible condenser entry temperature to the chiller. This approach results in extremely high power consumption of the auxillary equipment in the plant room while the energy saving impact on the chiller is minimal.

Specifically, this approach leads to the following:

1. Energy consumption of cooling towers and condenser pumps is excessively high.
2. Always running these equipment at full capacity makes them susceptible to breakdowns, lowering their operational life as well as inducing service interruptions.
3. Unnecessary operation of energy consuming machines at full capacities increases the carbon footprint of the chiller plant room.

Smart Joules is an Energy Saving Company(ESCO) determined to lower the operational costs of the chiller plant rooms across different hospital buildings and ensure that the chiller plant room operates under 0.72 ikW/TR without impacting the comfort of the building. The main reason behind exploring the scope of energy optimization of condenser water circuit in the water cooled chiller plant room is that by experimentations for optimizations the user end of the system remains unaffected. We are experimenting to find out the sweet spot of chiller operation from the condenser circuit perspective, where end user equipments like AHUs are not involved. This will eliminate any risks involving the user and the comfort he enjoys. Also conventionally the interventions in the condenser circuit of chiller plants is very minimal but the scope of savings is high compared to chilled water circuit.

METHODOLOGY

Chiller plant rooms are the largest consumer of energy in any building with centralised air conditioning system. Analysis reveal that more than 45% of the energy consumed in a building is for the centralised air conditioning plants with water cooled chillers comprising of chiller, chilled water pump, condenser water pump and cooling towers. The ideal plant room consumption sharing (Rahman et al., 2011) is shown in figure 1. In this pie chart we can see that the cooling towers and condenser water pumps together consume about 20% of the total chiller plant room consumption and also hold the key to maintain chiller performance in the optimum.

Most components within a chilled water system will benefit from variable speed drives. VFD costs have also decreased dramatically in the last several years. Variable speed pumping can provide an energy savings opportunity, but requires a close look at other parts of the system. On the chilled water side, a constant to variable flow retrofit may involve major and costly renovations of control valves and control sequences. Also, variable flow capabilities of existing/new chillers need to be reviewed. Low flow limits of the chiller may reduce the economic feasibility of variable chilled water pumping. On the condenser water side, variable flow control may be limited by chiller flow requirements or cooling tower fouling/freezing concerns. However, if pumps are oversized on a constant flow system, balancing pump flow by lowering speed versus flow restriction using a balancing valve may provide good payback. Further, continous optimization through operation of a variable speed condenser water pump opens a completely new dimension for energy savings. Cooling tower fans are another opportunity to save energy with VFDs. As loading and outdoor wet-bulb temperature decrease, variable speed fan motors not only save fan energy due to fan law benefits (a fan at 50 percent speed draws 12.5 percent of the power of a fan operating at 100 percent), but also provide more stable temperature control still operating at more than 50% efficiency (Bela G. Liptäk., 1995).

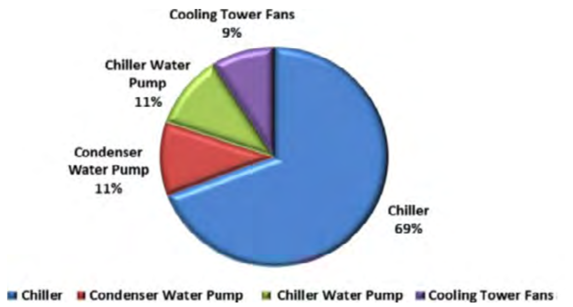

Figure 1: Equipment consumption sharing at 100% loading

Thus, the scope of savings in continuous condenser circuit optimization is evident in the analytical evaluation of a water cooled chiller plant room and the complexities involved in the realization of such an approach is also limited compared to the chilled water circuit optimizations. Condenser water pumps and cooling towers getting converted onto variable speed is only the beginning of the optimization process. There is a definite requirement of optimization strategy which would help us to maintain the chiller and chiller plant in the optimum efficiency. In the absence of such a strategy both these assets will be operated at full blast going with the conventional approach to get the minimum possible condenser entry, resulting in energy wastage.

We have conducted multiple experiments in hospital buildings managed by Smart Joules across India and have devised a strategy to manage the condenser circuit of the water cooled chiller plants in the best possible way so that we can eliminate energy wastage from the condenser water pumps and cooling towers.

Cooling tower approach based condenser circuit optimization

The operational efficiency or effectiveness of cooling tower is expressed by the equation:

$$\frac{Range}{Range + Approach} \qquad (1)$$

Where, range is the difference between cooling tower inlet temperature from the chiller and cooling tower outlet temperature to the chiller. Cooling tower approach is the difference between cooling tower outlet temperature to the chiller and ambient wetbulb temperature. The common designs of cooling towers are such that, bigger the cooling tower lesser will be approach, but this selection depends on the initial cost which can be invested as well as the operational requirments. Most commonly cooling towers give an approach of around 7˚F, means if wetbulb temperature of the area is measured to be 83˚F, then the best cooling tower outlet temperature we can get to the chiller is 90˚F if the cooling tower is fully loaded.

The operational strategy that we propose revolves around the cooling tower approach, which holds the key towards giving the chiller the best possible condenser entry temperature (Bela G. Liptäk., 1995). The maximum power consumption sharing for the condenser circuit including both the cooling towers and condenser pump should not exceed 20% of the total plant room consumption in an optimially operating plant room.

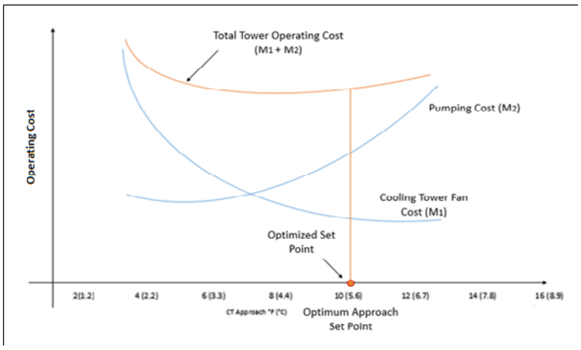

Figure 2: Approach Diagram; Condenser circuit operating cost with respect to cooling tower approach.

The above diagram depicts the relationship between cooling tower approach and operational cost of both the cooling tower and condenser water pump where:

- M_1 is the Cooling tower fan operating cost or cooling tower consumption.
- M_2 is the Condenser pump operating cost or condenser pump consumption.

From the diagram we can infer that when cooling tower approach is below 7°F then our cooling tower acts as a primary accelerator and condenser pump as secondary accelerator that means our cooling tower consumption should be higher than condenser pump consumption and when it is more than 7°F then vice-versa happens.. This is contrary to the existing strategy which was observed across many plant rooms in the country where we have seen that irrespective of approach delivered by the cooling tower both the condenser pump and the cooling tower is operated at full blast with the aim of getting minmum possible condenser entry temperature to the chiller leading to energy wastage.

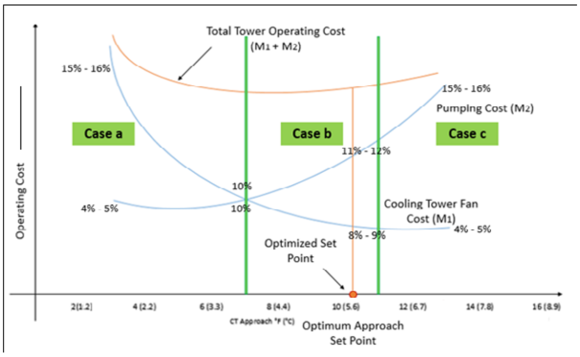

Figure 3: Approach Diagram; Case wise segregation

In our strategy to optimize the condenser circuits of water cooled chiller plants, we have divided the above figure 3 into three different zones based on the cooling tower approach obtained on site:

1. When the approach is below 7°F (3.8°C).
2. When the approach is in or near the optimum set point.
3. When the approach is more than 10.5°F - 11°F.

In all of the above conditions we will always maintain the minimum flow through the chiller condenser lines which is about 2.5 GPM/TR and ensure that the difference between condenser outlet temperature and condenser inlet temperature of the chiller is not increasing which would indirectly result in the increase of condenser inlet temperature to the chiller and resulting in energy wastage from chiller when we are trying to reduce condenser pump consumption. Let's anlyse each of these cases in detail:

1) When the approach is below 7°F (3.8°C)

When approach is below 7°F (refer figure 3), then as discussed above, cooling tower consumption should be higher than condenser pump consumption. This means we will lower down our condenser pump frequency to the minimum subjected to the flow requirements of the chiller and making sure we do not negatively impact condenser approach of the chiller and increase our cooling tower frequency(see table 1). After doing this, the percentage sharing for cooling tower should be around 15% - 16% and condenser pump should be 4% - 5% of the total plant room. These percentage sharings gives the idea about the way

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condenser circuit should be operated when cooling tower approach is towards the left side of the approach diagram(refer figure 3). This would eliminate all energy wastages due to the condenser pumps being operated at higher frequencies at all times irrespective of cooling tower apoproach.

Table 1:Operational Condition for case 1

CONDENSER PUMP FREQUENCY	COOLING TOWER FREQUENCY	CHILLER EFFICIENCY
30 Hz – 35 Hz	45 Hz – 50 Hz	< 0.54 kW/TR

2) When the approach is in or near the optimum set point

When the approach is between 7°F - 11°F, then as per the diagram, our condenser pump consumption should be little bit higher than cooling tower consumption(see table 2). The percentage sharing for cooling tower should be around 8% - 9% and condenser pump should be 11% - 12% of the total plant room in this case. When approach is 7°F, we consider equal consumption for both cooling tower and condenser pump that means 10% of the total plant room for both.

Table 2:Operational Condition for case 2

CONDENSER PUMP FREQUENCY	COOLING TOWER FREQUENCY	CHILLER EFFICIENCY
40 Hz – 45 Hz	38 Hz – 44 Hz	< 0.54 kW/TR

3) When the approach is more than 10.5°F - 11°F(6.5°C)

When the approach is more than 10.5°F - 11°F, then as discussed above our condenser pump consumption should be higher than our cooling tower consumption. During this condition, condenser pump frequency will be higher than cooling tower fan frequency(see table 3). At maximum operational frequency if cooling tower is not able to provide us approach lower than 10.5°F - 11°F, then it is more effective to invest in condenser water pump as WBT is also not in our hand. In this case already in the atmosphere water vapour content is high, so cooling tower is not able to work effectively to eject heat from the condenser water. Thus, it is not beneficial to invest on cooling tower beyond a certain point as it would not make any difference in the condenser entry temperature to the chiller and lead to energy wastage from the cooling towers. So, we ramp down the frequency of cooling towers observing the condenser entry temperature to the chiller. The percentage sharing for this case will be reverse from that of case ‘a’. In this case, condenser pump sharing will be around 15% - 16% and cooling tower sharing should be around 4% - 5%.

Table 3:Operational Condition for case 3

CONDENSER PUMP FREQUENCY	COOLING TOWER FREQUENCY	CHILLER EFFICIENCY
45 Hz – 50 Hz	30 Hz–45 Hz[1]	< 0.54 kW/TR

DISCUSSION AND RESULT ANALYSIS

We have conducted experiments across various sites and have identified different cases and validated this methodology with the actual data which we have collected from these sites through Smart Joules state of the art continous energy optimization platform, DeJoule. The following section aims to explain the results of the different experiments that we have conducted across different hopsital buildings managed by Smart Joules.

1) When the approach is below 7°F (3.8°C)

We observed this case at one of the hospital buildings managed by Smart Joules in Coimbatore which had the following chiller plant configuration:

- Two Variable Speed Screw Compressor Chillers of 434 TR and 172 TR.
- Two variable speed condenser pumps.
- One variable speed twin cell cooling tower of 700 TR and one constant speed cooling tower of 1000 TR.

Table 4:Design data for condenser pumps for site A

FLOW (GPM)	HEAD (METER)	POWER (kW)	FREQUENCY (Hz)
1050	20	16.01	50.5

Table 5:Design data for cooling towers for site A

RANGE (˚C)[2]	APPRO-ACH (˚C)[2]	POWER (kW)	FREQUENCY (Hz)
5	4	15	50

The approach and range in the above table means if cooling tower inlet from the chiller is 37˚C and wetbulb temperature of the area is measured to be 28˚C, then we will get a cooling tower outlet temperature to the chiller of 32˚C. From now on this site will be addressed as site ‘A’,from where we have collected chiller plant room data continously through

DeJoule. The operation of chiller plant which was in practise was as following, chilled water pump running

[1] subjected to calibration on site
[2] design data provided by the manufacturer

in 40 Hz – 45 Hz, condenser pump usually ran at 45 Hz with one twin cell cooling tower with one fan at 47 Hz and another at 50 Hz. The 434 TR chiller was running with a setpoint of 44°F. During this time the flow in the condenser circuit was observed to be 3 GPM/TR.

At this time condenser entry was 86°F during the day time and usually drops down to 83°F or below during the night. The condenser approach of the chiller and cooling tower approach was around 6°F and 3°F to 4°F respectively. The consumption which was recorded over a span of 24 hours with the above operational trend is given in Table 5.

Table 6:Consumption of condenser circuit for site A before the experiment

CT (kWh)	COND PUMP(kWh)	CHILLER (kWh)	PLANT ROOM(kWh)
370	**496**	**3,214**	**4,650**

The plant room consumption sharing of site A in the above condition was 8% on cooling towers, 11% on condenser pumps and 70.5% on chiller and the remaining on the chilled water pumps.

As per the above table our condenser circuit is consuming around 19% and chiller percentage sharing is coming ideal. But we know that when CT approach is below 7°F, then our condenser pump operating cost should be lower than the cooling tower operating cost. Please see the approach diagram for the site A.

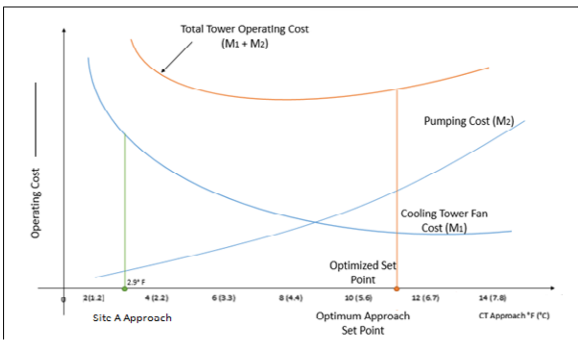

Figure 4: Ideal Approach Diagram with respect to Site A

Thus, we compared the case wise approach diagram (figure 3) with the data we collected and decided to maximize cooling tower fan speed to offer the chiller the least posssible condenser entry and reduce the condenser pump operating frequency to match it with our approach diagram. We have put condenser pump at 35 Hz and cooling tower fans at 49 Hz each. At the same time our chilled water pump was running at 40 Hz, left undisturbed.

As the cooling tower fan speed was increased the condenser entry got reduced by 1-2°F. Also, condenser approach is an important parameter as it determines how effectively heat transfer is taking place between water and refrigerant. It was also constant between 6°F and 7°F. The sharing of consumption was condenser pump consumption was 8.3%, cooling tower consumption was 11.65% and chiller consumption was 70.42% of the total plant room.

Table 7:Consumption of condenser circuit for site A after the experiment

CT (kWh)	COND PUMP (kWh)	CHILLER (kWh)	PLANT ROOM (kWh)
467	**367**	**3,087**	**4,393**

The impact this change created in terms of energy consumption is tabulated in table 7, where we can see that increasing cooling tower fan speed has provided lower condenser entry temperature leading to decrease in consumption of the chiller. At the same time lowering the condenser pump frequency has yielded substantial savings from the condenser pump as well. We computed a daily savings of 250-280 kWh from the chiller plant as a result of this resulting to a monthly increment in savings of the entire site by 9-10%.

2) When the approach is below 4°F (2.4°C)

We observed this case at one of the hospital buildings managed by Smart Joules in Delhi which had the following chiller plant configuration:

- One Variable Speed Screw Compressor Chiller of 350 TR.
- One variable speed condenser pump.
- Two variable speed cooling towers of 300 TR and one constant speed standby cooling tower of 300 TR.

Table 8:Design data for condenser pump for site B

FLOW (GPM)	HEAD (METER)	POWER (kW)	FREQUENCY (Hz)
1050	**20**	**16.01**	**50.5**

Table 9:Design data for cooling towers for site B

RANGE (˚C)[1]	APPRO-ACH (˚C)[1]	POWER (kW)	FREQUENCY (Hz)
5	**4**	**10**	**50**
5	**4**	**15**	**50**

The approach and range in the above table means if cooling tower inlet from the chiller is 37˚C and wetbulb temperature of the area is measured to be 28˚C, then we will get a cooling tower outlet temperature to the chiller of 32˚C.

From now on this site will be addressed as site **'B'**, from where we collected chiller plant room data continously through DeJoule. The operation of chiller plant which was in practise was as following, 350 TR chiller runs with one condenser pump, one chilled water pump and two cooling towers. Usually, condenser pump ran at 40 Hz – 45 Hz, with chilled water pump running at 40 Hz and both cooling towers at 40 Hz and 40 Hz respectively.

Table 10:Consumption of condenser circuit for site B before the experiment

CT (kWh)	COND PUMP (kWh)	CHILLER (kWh)	PLANT ROOM (kWh)
386	**333**	**2,033**	**3,042**

The sharing of consumption was condenser pump consumption was 10.95%, cooling tower consumption was 12.65% and chiller consumption was 68.47% of the total plant room and the remaining for the chilled water pump.

During this time our condenser pump was running in 45 Hz and both cooling towers were running at 40 Hz and condenser entry was maintaining around 80°F. The cooling tower approach is around 1°F - 2°F and condenser approach was 5°F on average. Set point was 45°F throughout the day. Chiller efficiency on this day was 0.511 kW/TR and chiller plant efficiency was 0.778 kW/TR. As per the percentage sharing, our condenser circuit is consuming more than 20% which is not following the optimum. Chiller consumption is according to the ideal sharing of the plant room. On comparing with the case wise approach diagram(figure 3) there was variation on power distribution on the condenser pumps and cooling towers with respect to the actual approach observed in the data collected for the site B through DeJoule(refer figure 5). Thus, we tried to match our cooling tower operating cost with the ideal approach diagram by ramping both the cooling towers frequency up to 40 Hz and to minimize the condenser pump consumption, we ramped down the frequency of condenser pump to 35. After this has been done the sharing of consumption was condenser pump consumption was 6.2%, cooling tower consumption was 12.57% and chiller consumption was 72.48% of the total plant room and remaining of the distribution for the chilled water pump.

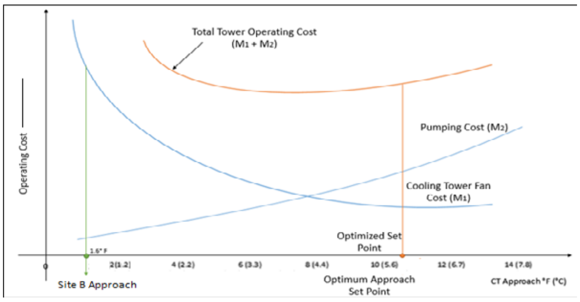

Figure 5: Ideal Approach Diagram with respect to Site B

The impact this change has created in terms of energy consumption is tabulated in Table 11. During this time condenser entry was around 78°F and condenser approach maximum rises to 5.5°F only.

Table 11:Consumption of condenser circuit for site B after the experiment

CT (kWh)	COND PUMP(kWh)	CHILLER (kWh)	PLANT ROOM(kWh)
351	**193**	**2,255**	**3,072**

On this day, set point management was also done. It varies from 44°F to 48°F. Chiller efficiency on this day was 0.48 kW/TR and chiller plant efficiency was 0.687 kW/TR. As per the percentage sharing, condenser circuit is consuming 19% which is according to the ideal scenario. But chiller consumption has slightly increase as per the percentage sharing.

If we compare Table 10 and 11 we can see that we are saving 140 kWh from condenser pump by ramping down the frequency but we are incurring 172 kWh extra on chiller although the chiller efficiency and chiller plant efficiency is better than earlier. This is due to the reason that there is difference in Tonnage(TR) delivery. In the earlier case the Tonnage(TR) delivery is less that is why we are getting less kW/TR but in the latter situation, we are providing more cooling with an additional 30 kWh only. If same amount of Tonnage(TR) has been produced in the day before the experiment, then the chiller consumption would have been much higher. Moreover condenser entry and condenser approach remains the same throughout the day of the experiment. We computed a daily savings of 150-180 kWh from the chiller plant as a result of this experimentation and this was actually adopted as a standard operating procedure at the site, resulting to a monthly increment in savings of the entire site by 11-12%.

3) When the approach is more than 10°F(6.5°C)

We observed this case at one of the hospital buildings managed by Smart Joules in Vishakapatnam which had the following chiller plant configuration:

- One variable speed screw compressor chiller of 160 TR.
- One variable speed condenser pump.
- Two variable speed cooling tower of 100TR.

Table 12:Design data for condenser pump for site C

FLOW (GPM)	HEAD (METER)	POWER (kW)	FREQUENCY (Hz)
550	**18**	**11**	**50**

Table 13:Design data for cooling towers for site C

RANGE (˚C)[1]	APPRO-ACH (˚C)[1]	POWER (kW)	FREQUENCY (Hz)
5	**4**	**15**	**50**

The approach and range in the above table means if cooling tower inlet from the chiller is 37˚C and wetbulb temperature of the area is measured to be 28˚C, then we will get a cooling tower outlet temperature to the chiller of 32˚C.

From now on this site will be addressed as site **'C'**, from where we collected chiller plant room data continously through DeJoule. The operation of chiller plant which was in practise was as following, chilled water pump running in 40 Hz – 45 Hz, condenser pump usually ran in at 45 - 50 Hz with both cooling towers operating at 50 Hz. The 160 TR chiller was running with a setpoint of 48°F. During this time the flow in the condenser circuit was observed to be 3 GPM/TR.

During this period condenser entry was observed to be around 89 - 91°F during the day time and usually drops down to 86°F or below during the night. The condenser approach of the chiller and cooling tower approach was around 6°F and 9°F to 11°F respectively. The consumption which was recorded over a span of 24 hours with the above operational trend is given in Table 14.

The sharing of consumption was condenser pump consumption was 13.66%, cooling tower consumption was 8.62% and chiller consumption was 70.88% of the total plant room and the remaining for the chilled water pump.

Table 14:Consumption of condenser circuit for site C before the experiment

CT (kWh)	COND PUMP (kWh)	CHILLER (kWh)	PLANT ROOM (kWh)
144	**228**	**1,159**	**1,669**

As per the above table our condenser circuit is consuming around 20.84% and chiller percentage sharing is around 71%. But we know that when cooling tower approach is above 10°F, then our condenser pump operating cost should be higher than the cooling tower operating cost as well as the total energy invested on the condenser circuit should not exceed 20% of the overall chiller plant consumption. Please see the approach diagram for the site C.(figure 6)

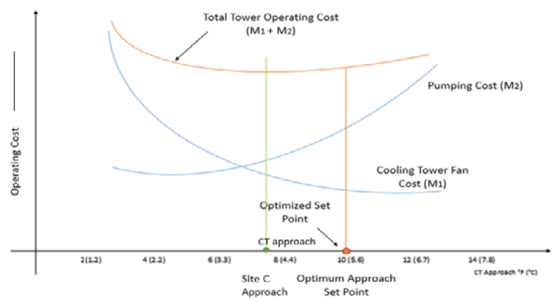

Figure 6: Ideal Approach Diagram with respect to Site C

Thus, we compared the case wise approach diagram(figure 3) with the data we collected and decided to provide the maximum flow possible to the condenser circuit to enable maximum heat transfer. At the same time cooling tower approach was higher towards the right side of the approach diagram(figure 6), which means injecting more power onto the cooling tower is not giving us any impact on the condenser entry temperature to the chiller from the cooling tower. This might be due to the high wetbulb temperature of the area or due to the fact that cooling tower is inefficient. Hence, we put condenser pump at 50 Hz, delivering maximum flow of 550 GPM and cooling towers at site were calibrated such that frequencies were ramped down in steps of 1 Hz from

49 Hz for both the cooling towes to find out the point where condenser entry temperature to the chiller is starting to change. The condenser entry temperature to the chiller was 88˚F at the beginning of the experiment and remained so till both the cooling towers were operating at 35Hz, below which it was affecting the condenser entry temperature. Thus, we locked both the cooling towers at 35Hz. At the same time our chilled water pump was running at 40 Hz, left undisturbed.

The sharing of consumption was condenser pump consumption was 14%, cooling tower consumption was 6.62% and chiller consumption was 70.65% of the total plant room.

Table 15:Consumption of condenser circuit for site C before the experiment

CT (kWh)	COND PUMP(kWh)	CHILLER (kWh)	PLANT ROOM(kWh)
108	230	1,151	1,601

The impact this change created in terms of energy consumption is tabulated in table 14, where we can see that decreasing the cooling tower speed from maximum to 35 Hz did not create any impact on the chiller consumption as condenser entry temperature to the chiller remained constant during the entire course of the experiment. The condenser pumps were running at maximum frequency delivering maximum flow through the condenser lines of the chiller to ensure maximum heat transfer between the refrigerant and cooling water. We computed a daily savings of 70-80 kWh from the chiller plant as a result of this experimentation and this was actually adopted as a standard operating procedure at the site(subjected to ambient climatic conditions), resulting to a monthly increment in savings of the entire site by 3-4%.

CONCLUSION

Centralized cooling systems in India waste 40% of the 15 billion kWh of energy they consume because of inefficient system designs and equipment, and suboptimal operational practices. This paper proposes a data driven approach towards continous optimization of condenser circuit of the water cooled chiller plants. The proposed methodology based on the cooling tower approach have been explained in detail with three different cases. The strategies to be formulated differs in all the three cases which considers the constraints such as altering any parameters should not affect overall chiller and chiller plant effciency. In all the cases condenser approach and chiller performance should not be affected by the operational optimizations.

These cases were validated with experiments and it was found that both the cooling towers and condenser pumps needs to be operated in a dynamic way based on the cooling tower approach. This was contrary to the existing methodology where both these assets were operated at full blast at all operating conditions with an aim to achieve the best possible condenser entry temperature to the chiller. The proposed methodology has resulted in eliminating substantial energy wastage from the condenser circuit as well as from the chiller. We have observed an improvement in overall energy savings of the project sites of 5% to 12% on account of this optimization strategy. INR 5,000 Crore worth of energy can be saved in India by optimizing central cooling systems across industries, of which atleast 5-10% can be captured by this continuous operational optimization strategy.

Apart from energy savings we captured through this optimization technique, we also achieved reduction in the Carbon Dioxide emissions[3] by 80 tonnes through site A energy savings, 50 tonnes through site B and 20 tonnes through site C in one year. Apart from making all the equipment's variable speed, these processes demands a dynamic control derived through a data driven approach which can be realized through a continous energy optimization platform. This will open up a completely new dimension for energy savings and CO_2 reduction in water cooled chiller plants.

NOMENCLATURE

VFD = Variable frequency drive
GPM = Gallon per minute
TR = Tonnage of Refrigeration
CT = Cooling Tower
COND = Condenser Pump

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[3] 1MWh is equivalent to 0.82 tonnes of CO_2

ENERGY EFFICIENCY FOR
BUSINESS COMPETITIVENESS

FACTORS INFLUENCING ENERGY DEMAND AND GHG EMISSIONS FROM INDIAN MANUFACTURING – AN LMDI DECOMPOSITION STUDY

Tirtha Biswas[1], Deepa Janakiraman[2], Karthik Ganesan[3]

[1]*Council on Energy, Environment, and Water (CEEW)*
New Delhi, India
tirtha.biswas@ceew.in

[2] *Council on Energy, Environment, and Water (CEEW)*
New Delhi, India
deepa.janakiraman@ceew.in

[3] *Council on Energy, Environment, and Water (CEEW)*
New Delhi, India
karthik.ganesan@ceew.in

ABSTRACT

The manufacturing sector is the single largest consumer of delivered energy – accounting for 36% of total final energy consumption (TFEC) in the Indian economy. While energy efficiency is now a mainstream pursuit, increasing economic activity has driven up energy consumption in the sector. The future energy demand of the sector is set to increase to 44% by 2040.

Using unit-level data from the Annual Survey of Industries, this study traces activity and energy use in manufacturing firms for the period 2004 – 2015. Specifically, the pre-PAT (pre FY13) and PAT (FY13 – FY15) periods are compared through a decomposition of energy consumption and GHG emissions using the Logarithmic-Mean Divisia Index (LMDI) method. The main objective was to evaluate whether the PAT scheme has enhanced the role of energy efficiency.

The energy decomposition analysis indicated that the during the PAT period, the impact of energy efficiency was nearly double that of the pre-PAT period. However, the shift in the industry structure – to more energy intensive sectors, had a much more telling effect on energy consumption. Declining industrial activity in the PAT period contributed significantly to reducing emissions and energy demand. The fuel-mix of input energy has remained constant and coal remains the mainstay throughout. An expansion of the PAT scheme by lowering thresholds for inclusion, would be beneficial, but targets have to be much more aggressive for the increased administrative costs to pay-off. A concerted focus on fuel-switching can be a key driver of mitigation efforts in the industrial sector.

Keywords— PAT, ASI, decomposition, energy efficiency, emissions intensity

INTRODUCTION

Manufacturing sector is the single largest consumer of delivered energy and contributes to a large share of emissions as well. The sector consumes around 36% of total final energy consumption (TFEC) by end users of the economy (IEA, 2018). At a sub-sectoral level, our estimates indicate that 3 sectors – iron & steel, cement, and chemical & fertilisers contribute together consume ~ 65% of the total energy supplied to the sector (Figure 1).

During the period 2005 to 2015, the TFEC of the manufacturing sector increased from 89 MTOE in 2015 to 166 MTOE in 2015 with a rate higher than that of the overall economy. In 2015, the iron & steel industry was the major contributor to the growth in energy demand during the period, roughly contributing to 37% of the increase in demand. Non-metallic minerals, non-ferrous metals and chemical & fertiliser industries together contributed another 33% to the increase in demand. The economic growth of these sectors is driven by national policies that support economic development and increasing the standards of living in the country.

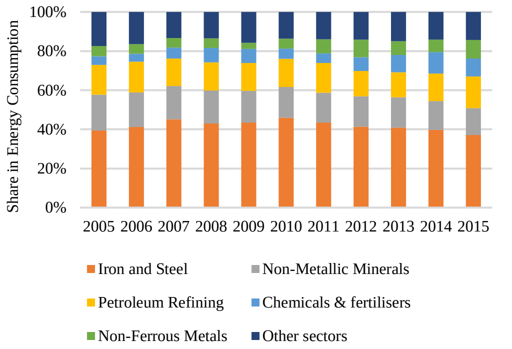

Figure 1: Energy consumption trend in manufacturing sector

The national steel policy targets a 3-fold increase in steel manufacturing capacity to increase the present per capita steel consumption levels from ~ 65 kg to 130 kgs by 2030 (Worldsteel, 2018). Increasing income levels would also lead to higher per-capita consumption levels of cement, and petrochemical products thus warranting further investments in their production capacities.

Our estimates indicate that energy intensity decreased with an annual rate of 2% between 2005 to 2015, primarily driven by the market competitive forces. However, the rate is not aggressive enough to decouple the energy demand from economic growth. The World Energy Outlook's central scenario (NPS) estimates the future energy demand by the sector to increase to 44% by 2040 (IEA, 2018).

In an effort to improve the energy efficiency of the industrial sector, Bureau of Energy Efficiency (BEE) implemented the Perform, Achieve and Trade scheme (PAT) – a market-based mechanism nudging industries towards energy efficiency improvements of their production processes. The first cycle of PAT, implemented between FY13 and FY15, covered 334 manufacturing units (also known as DCs) and 144 thermal power plants. While outcome of the scheme indicates that the majority of the manufacturing units overachieved their given targets, the resultant energy savings was only 5.61 MTOE – roughly representing 3% of total sector's energy consumption (BEE, 2018).

One major limitation of the scheme is in scaling up to cover the entire industrial sector. The present scope of PAT scheme is limited to the large-scale enterprises and has very high transaction costs – roughly representing a budgetary expenditure of INR 0.4 crore per enterprise (Standing Committee on Energy, 2014). The subsequent cycles of the scheme are expected to achieve a further reduction of 9.18 MTOE between FY16 and FY20 but, the industries covered in these cycles still represent 60% of the energy consumption in the sector. Further, the incremental savings targeted by the scheme significantly reduces from 6.97 MTOE targeted in FY17 – FY19 to just 0.5 MTOE targeted in FY20- FY22.

OBJECTIVE

For policy planners, it is important to understand the underlying drivers of energy demand and the resulting emissions. In the short-run, it is expected that overall energy use and emissions will continue to grow. Any attempt to make the processes more efficient and to decarbonise manufacturing would require an understanding of the contributing factors. A decomposition analysis of energy demand and from the manufacturing sector has been undertaken to provide some direction on this matter.

We aim to understand and evaluate the impact of the PAT scheme on the overall manufacturing sector by comparing the key drivers of energy demand and emissions across the pre-PAT (FY05 to FY12) and PAT (FY13 to FY15) periods. It is an extension of our previous analysis on determinants of energy demand and associated carbon emissions form indian manufacturing firms for the period 2004 – 2014 using the logarithmic-mean divisia index (**LMDI**) method (Biswas, et al., 2016). The previous analysis explained the increase in energy demand by looking at the underlying factors – impact on energy demand and emissions due to increased economic activity, structural changes within the sector, energy efficiency improvements, changes in the energy mix and their corresponding emission factors.

METHODOLOGY

The Index Decomposition Analysis (IDA) is a widely used technique for analysing the changes in energy consumption. It is used to analyse the impact of economic, environmental and technological parameters on overall consumption levels using historical data. The use of IDA dates back to 1970s when a sudden rise in oil prices demanded a need to evaluate the historic energy consumption pattern, so as to understand the underlying drivers of price shock, and to forecast the future demand. It was first used by the United States (Myers & Nakamura, 1978) and United Kingdom (Bossanyi, 1979). In the 1990s, IDA was used by researchers to analyse the increasing greenhouse gases and drivers behind global warming. This paper uses the IDA technique to analyse factors

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that affect increase or decrease in energy demand in the manufacturing sector.

The total energy consumption of the manufacturing sector at any point of time can be expressed as a function of overall activity of the manufacturing sector, share of activity of individual sub-sectors and their respective energy intensities. The basic identity can be expressed as follows:

$$E = \sum_i E_i = \sum_i \left(\frac{Q_i}{Q}\right) * \left(\frac{E_i}{Q_i}\right) * Q = \sum_i Q * S_i * I_i \quad (1)$$

Similarly, IDA identity in equation 1 can be extended to decompose the emissions associated with the energy use. The equation (Equation 2) is similar to the previous one except two additional factors – energy mix of industrial sectors, and the corresponding emission factors of the fuels in the energy mix.

$$C = \sum_{i,j} C_{i,j} = \sum_{i,j} Q \left(\frac{Q_i}{Q}\right) * \left(\frac{E_i}{Q_i}\right) * \left(\frac{E_{ij}}{E_i}\right) * \left(\frac{C_{ij}}{E_{ij}}\right) = \sum_{i,j} Q * S_i * I_i * M_{ij} * U_{ij} \quad (2)$$

The change in total energy consumption and emissions between base year (t) and target year (T) can be perfectly decomposed by three explanatory variables.

$$E^T - E^t = \Delta E = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} \quad (3)$$

$$C^T - C^t = \Delta C = \Delta C_{act} + \Delta C_{str} + \Delta C_{int} + \Delta C_{mix} + \Delta C_{emf} \quad (4)$$

Activity Effect (ΔE_{act} or ΔC_{act}): Accounts for the change in **energy consumption or emissions** attributed to change in overall activity of the manufacturing sector

Structure Effect (ΔE_{str} or ΔC_{str}): Accounts for the change in **energy consumption or emissions** attributed to change in activity share of individual manufacturing sub-sectors.

Intensity Effect (ΔE_{int} or ΔC_{int}): Accounts for the change in **energy consumption or emissions** attributed to change in energy intensities (expressed as energy consumption per unit of output in monetary terms) of individual manufacturing sub-sectors.

Energy-mix Effect (ΔC_{mix}): Accounts for the change in **emissions** attributed to change in energy mix of individual manufacturing sub-sectors.

Emission Factor Effect (ΔC_{emf}): Accounts for the change in **emissions** attributed to change in carbon emissions factors of the fuel consumed within individual manufacturing sub-sectors.

Laspeyres and Divisia indices are two of the popular techniques used to estimate the decomposition factors. In the Laspeyres index, the impact of one variable on the dependent variable is calculated by keeping the other explanatory variables constant. This method often leaves a residual value which is interpreted as the interaction effect between the variables. Further, there are no obvious linkages between the additive and multiplicative decompositions.

The Divisia index was originally developed as a substitute for the laspeyres index. It measures the impact of the variables simultaneously by the weighted averages of their respective relative logarithmic growth rates between the base and target years. This paper uses the logarithmic mean divisia index – I (LMDI-I) method, which helps in meeting the factor-reversal tests and leaves no residuals. A number of studies in the past have used LMDI-I technique for decomposition. Specifically in India, (Reddy & Ray, 2010), (Sahu & Narayanan, 2010) and (Ghosh, et al., 2014) have used the LMDI-I technique to analyse energy consumption in the manufacturing sector. The additive decomposition was introduced in (Ang, et al., 1998) while the multiplicative decomposition was demonstrated in (Ang & Liu, 2001) where the authors decomposed the ratio of change with respect to the base year.

The decomposition factors, using the LMDI-I technique can be expressed as follows:

Equation 5: Additive decomposition of Energy	Equation 6: Additive decomposition of emissions
$\Delta E_{act} = \sum_i w_i \ln \frac{Q^T}{Q^t}$ $\Delta E_{str} = \sum_i w_i \ln \frac{S_i^T}{S_i^t}$ $\Delta E_{int} = \sum_i w_i \ln \frac{I_i^T}{I_i^t}$ $W_i = \frac{(E_i^T - E_i^t)}{(\ln E_i^T - \ln E_i^t)}$	$\Delta C_{act} = \sum_i w'_i \ln \frac{Q^T}{Q^t}$ $\Delta C_{str} = \sum_i w'_i \ln \frac{S_i^T}{S_i^t}$ $\Delta C_{int} = \sum_i w'_i \ln \frac{I_i^T}{I_i^t}$ $\Delta C_{mix} = \sum_i w'_i \ln \frac{M_{ij}^T}{M_{ij}^t}$ $\Delta C_{emf} = \sum_i w'_i \ln \frac{U_{ij}^T}{U_{ij}^t}$ $W'_i = \frac{(C_i^T - C_i^t)}{(\ln C_i^T - \ln C_i^t)}$

DATA SOURCES

The Annual Survey of Industries (ASI), a survey conducted by Central Statistics Office (CSO) Industrial Statistics (IS) wing, is the principal source of data on input and output of registered manufacturing sector in India. ASI is the principal source of Industrial Statistics in India and plays a key role in assessing the changes in the growth and structure of the registered units in the manufacturing sector.

ASI is a combination of census and survey approaches. The distinction between census and survey is done using multipliers, where a multiplier of one represents a census factory while a multiplier greater than one represents a survey factory. The multipliers of survey factories are indicative of the number of units they represent. ASI, through its collection of factory inputs, collects time series data on fuel and material consumption of individual units (MoSPI, 2019). This analysis only considers formal manufacturing industries registered under section 2m (i) & (ii) of factories act.

The use of ASI presents varied challenges, as many errors are observed at the unit level while looking at the data more intricately. For instance, some factory units report incorrect multipliers. As a convention, we assign a multiplier of one to all factories with employment greater than 100. Another major error with the dataset revolves around reported rates by manufacturing units for their inputs. The erroneous rates, if not corrected will have a major implication on the estimated energy and emissions from these factors (Figure 2). Logical assumptions have been made to correct these erroneous entries and the steps are listed below:

- First, different units of measurement (UoM) adopted by certain factories has been standardized to a common UoM for each fuel type across industries over the assessment period.
- Second, factories which are common over a period of time, mostly the bigger operations, and are consistent with reported rates and UoMs, have been considered to arrive at a median rate for each fuel type. These median rates are further used to define permissible bounds for the outlier values when the entire dataset is analysed.
- Third, common factories within two different time frames (FY05 to FY10, and, FY11 to FY15) were considered for defining median rates to account for new additions, closure or expansion of manufacturing activities.
- Fourth, creating of **benchmark rates**. To mimic the heterogeneity with manufacturing process across the country, median rates were defined considering three distinct layers: (a) median rates at a sector level; (b) median rates at state level; and, (c) median rates at the national level. The choice of defining bounds is suitably made after considering adequate number of representative industries within each state.
- Finally, A generous variation of 50% (in either side) is allowed between the reported rate and the **benchmark rate** for each fuel type as a scrutiny measure. This is to accommodate higher costs incurred on transporting fuels in certain geographic locations.

A sensitivity analysis was performed using the **benchmark rates** to check for the robustness of these assumptions (Figure 2). The results show that without applying any rate corrections emission estimates vary between -1% and 5% compared to the corrected estimates. Creation of benchmark rates using the 30th percentile and 40th percentile values instead of the median from the rate distributions for each fuel type leads to a variation of the estimated emissions to a maximum of 4% and 2% respectively. Using both the 60th percentile and 70th percentile values instead leads to a maximum variation of 1%. Overall the variation of emissions estimates with the variation of benchmark rates remains less than 5%. Thus, highlights the robustness of the assumptions.

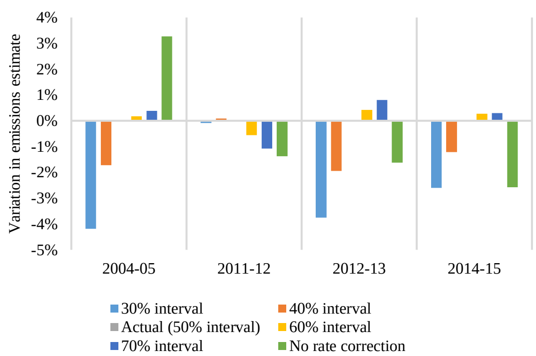

Figure 2: Sensitivity analysis of emissions with variations in benchmark rates

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ASI provides information on the National Industrial Classification (NIC) code that every unit falls under. For the analysis, enterprises have been grouped into 11 sub-sectors using their NIC codes (refer Annexure 1). Certain sub-sectors have been omitted due to insufficient data within the ASI database. These sectors are manufacture of solid fuels, other energy industries, petroleum refining, mining, and construction. One can possibly attribute this to the lack of an updated survey frame thus leading to poor representation especially in these sectors (Dholakia, et al., 2015).

In order to maintain a uniform panel across the years, only common factories between FY05, FY12, FY13 and FY15 have been considered. It was found that only 7581 factories are common for these years out of roughly 2 lakh factories surveyed annually. Hence, with a share in total energy consumption of more than 60%, this study presumes that these common factories would reflect the average trend of the entire industry sector.

The energy consumption by these factories are estimated by considering more than 80 different fuel types and grid electricity consumption as reported. Their corresponding emissions are estimated by considering calorific values and emission factors obtained from official sources and IPCC guidelines (Gupta, et al., 2019). Further, the economic activity of the factories and their respective sectors, the total output from the enterprises have been estimated by multiplying unit cost of sales (inclusive of distributive expenses) with physical quantities of manufactured products.

RESULTS

As described before in the methodology section, the three main factors that determine the level of energy consumption and emissions in an economy are: overall activity or production levels, structure of the economy, the output per unit of energy use, energy mix of the industrial sectors and the corresponding carbon emission factors of fuels in the energy mix. During the pre – PAT period (FY05 to FY12), energy consumption by the common factories has increased by 19.36 MTOE. As for the additive decomposition (Table 1), the increase in industrial activity (expressed as production output) has led to an increase in energy demand by 33.60 MTOE. The structural transition away from the high energy intensive manufacturing has reduced the energy demand by 9.75 MTOE. Energy efficiency improvements by the factories also reduced the energy demand by 4.49 MTOE.

Factors	Pre-PAT period (FY05 – FY12)	PAT period (FY13 – FY15)
ΔE	19.36	-0.32
ΔE_{act}	33.60	1.77
ΔE_{str}	-9.75	1.36
ΔE_{int}	-4.49	-3.45

Table 1: Additive decomposition of energy demand (MTOE)

The PAT period, overall was one of subdued growth in industrial activity among the common factories captured. During, in the PAT period (FY13 to FY15), there was virtually no increase in net energy consumption (Table 1). While, the increase in activity and structural shift towards energy intensive manufacturing increased the energy demand by 1.77 MTOE and 1.36 MTOE, it was offset by reduced output levels and improvements in the energy intensity of production.

The results from decomposition analysis of emissions indicate that in the pre-PAT period, emissions increased by 96.80 MtCO2eq (Table2). Activity effect and energy-mix effect increased the emissions by 159.97 MtCO2eq and 9.60 MtCO2eq respectively. While, structure effect, intensity effect, and emissions factor effect reduced the emissions by 44.13 MtCO2eq, 22.94 MtCO2eq, and 5.71 MtCO2eq respectively. During the PAT period, emissions reduced by 9.45 MtCO2eq, primarily due to low levels of production output and reduction in the energy intensity of production compared to the pre-PAT period.

Factors	Pre-PAT period (FY05 – FY12)	PAT period (FY13 – FY15)
ΔC	96.80	-9.45
ΔC_{act}	159.97	8.27
ΔC_{str}	-44.13	7.04
ΔC_{int}	-22.94	-22.74
ΔC_{mix}	9.60	0.78
ΔC_{emf}	-5.71	-2.80

Table 2: Additive decomposition of GHG emissions ($MtCO_2eq$)

Comparing The Decomposition Factors For Emissions During The Pre-PAT And PAT Periods

The following section analyses the factors (from additive decomposition) of emissions across the periods. Given the difference in the number of years the periods represent, explanatory factors have been annualized for comparison (Figure 3).

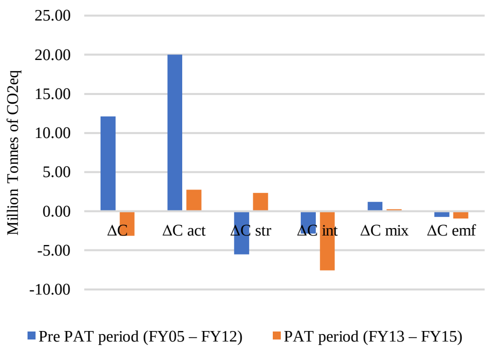

Figure 3: Comparison of annualized decomposition factors between pre-PAT and PAT periods

Activity effect.

The factories analysed during the pre-PAT period showed considerable growth in industrial activity when compared to the PAT period, as indicated by the CAGR of 9% and 1% respectively. The decreasing trend of the manufacturing output during the PAT period is also reflected in the Index of Industrial Productivity (IIP) indices, indicating a downward trend in industrial production post FY13 (MoSPI, 2018). The rise in the policy rates coupled with the bottlenecks facing large projects took its toll on the investments. Due to low level of investment in R & D, India has not seized the opportunities available in the growing sub-sectors such as chemicals, machinery & equipment, electrical machinery, electronic goods, etc. Overall, growth in manufacturing sector also suffered on account of the negative spill-over from the mining and capital goods segment, lower demand for consumer goods including durables, structural constraints of some sectors such as fertilisers etc. (DEA, 2014).

Structure effect.

The negative impact (on emissions) of structure effect in the pre-PAT period was primarily due to the reduction in share of high energy intensive sub-sectors (iron & steel, non-ferrous metals, and non-metallic minerals) in the total manufacturing production output. The share of the three sub-sectors reduced from 29% in FY05 to 22% in FY12. Correspondingly, the share of low energy intensive sub-sectors, such as machinery, increase from 12% in FY05 to 15% in FY12. This resulted in lower demand for energy inputs and emissions levels. The structure effect led to an annual decrease of energy consumption and emissions by 1.22 MTOE and 5.52 MTCO2e respectively during the period (Figure 3). However, for the PAT period the structure effect had a positive impact in overall energy consumption and emissions increasing it annually by 0.45 MTOE and 2.35MTCO2e respectively (Figure 3). This is primarily due to the falling share of output from the low energy intensive sub-sectors from 15% in FY13 to 13% in FY15. On the other hand, the high energy intensive sub-sectors indicated a marginal increase from 22% in FY13 to 23% in FY15.

Intensity effect.

The reduction of energy intensity has been observed to be higher in the PAT period (-1.15 MTOE) as compared to the pre-PAT period (-0.56 MTOE). This resulted in lower levels of emissions during the PAT compared to the pre-PAT period (Figure 3). However, the reduction in energy intensity has not been observed across all sub-sectors but is primarily driven by the iron & steel and non-ferrous metals.

Table 3 highlights the energy intensity of production output of the manufacturing sub-sectors for the PAT period. The highest reduction in energy intensity was shown by the non-ferrous metals industries. The energy intensity of production of the sub-sector decreased from 18 TOE/Million INR in FY13 to 10 TOE/Million INR in FY15, indicating a 43% reduction during the period. In case of iron & steel sub-sector, the energy intensity decreased from 21 TOE/Million INR in FY13 to 18 TOE/Million INR in FY15. While in absolute terms the reduction is only 12%, the impact on overall manufacturing sector is significant because the sector alone contributes to ~ 40% of energy demand by the manufacturing sector.

Energy Intensity of production output (TOE/Million INR)		
Industry Sector	**FY13**	**FY15**
Chemicals & fertilisers	3.49	5.94
Food processing, beverages and tobacco	1.00	1.01

Iron & steel	20.79	18.30
Machinery	0.51	0.37
Non-ferrous metals	17.96	10.21
Non-metallic minerals	19.19	20.12
Non-specified industry	0.98	0.69
Pulp, paper and print	10.37	10.81
Textile and leather	3.06	2.77
Transport equipment	0.46	0.32
Wood and wood products	1.60	1.24

Table 3: Energy Intensity trend of sub-sectors in the PAT period

Transport equipment and machinery sub-sectors also indicated ~ 30% reduction in energy intensity, however their share in overall energy consumption remained low. Only chemicals & fertilizer industries indicated a significant increase in energy intensity during the period. While for remaining sectors (except non-specified industries) the change in energy intensity remained within 10%.

Energy-mix effect.

Energy-mix was found to have a positive impact on the emissions (in both periods) primarily due to the fact that ~ 78% of the energy requirement is met by coal. During the pre-PAT period, coal and lignite, grid electricity, natural gas, and petroleum fuels represented ~ 78%, 10%, 1%, and 11% respectively. Similarly, in the PAT period, coal and lignite, grid electricity, natural gas, and petroleum fuels represented ~ 78%, 10%, 5%, and 7% respectively.

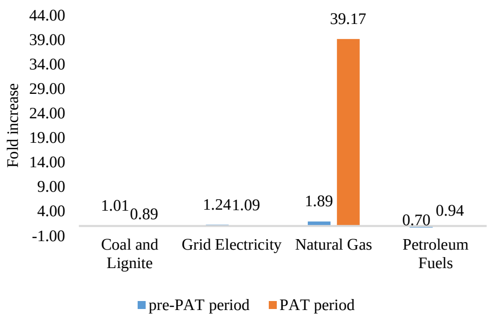

Figure 4: Comparison of industrial energy-mix between pre-PAT and PAT periods

In the PAT period, energy-mix had a much lower impact on emission. Natural gas replaced a fair share of coal and petroleum fuels in the energy-mix. Figure 4, shows that in the PAT period, share of natural gas in the energy mix increased by more than 30 folds compared to a ~ 2-fold increase during the pre-PAT period. However, the consumption of natural gas was largely limited to the chemicals and petrochemicals sector in both the periods.

Emission factor effect.

In the analysis, the emissions factor for all fuels virtually remain unchanged as these are more or less invariant. Two emission factors are country specific and liable to change frequently. One is coal used in the economy and the other for the emission factors associated with the production of electricity. For coal, India has not reported different EFs over the years and we use nationally consistent factors. A closer look at the grid emission factors indicates a steady increase in the share of non-fossil fuel-based electricity generation (Figure 5). A marginally higher impact of the factor during the PAT period is a result of a higher rate of increase in generation from non-fossil fuel during the period.

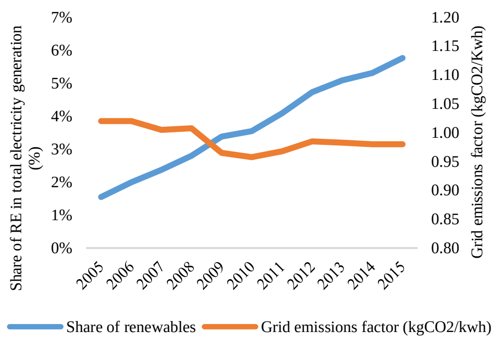

Figure 5: Trend of grid emissions factor and renewable (solar, wind, and biomass) electricity generation

Summing up the comparison, it was observed that the PAT scheme did have a higher impact on reducing emissions during its implementation period. However, majority of the reduction in emissions resulted from the decrease in industrial output during the period. This indicates that the industrial emissions in have grown in lockstep with the economic growth of the sector (Biswas, et al., 2016). The only mitigation policy targeted towards the sector – PAT, currently covers 60% of the energy consumption in the sector. Expanding the scheme to the entire sector would require a careful evaluation of the benefits (in terms of energy savings) and associated transaction costs.

Evaluation Of PAT Scheme – Existing Coverage And Potential For Further Expansion

Analysing the distribution of energy consumption in the manufacturing sector indicates that the top 10th percentile of the number of enterprises represent ~ 90% of total energy consumption in the sector. These enterprises had an average turnover of INR 663 crore, and ~ 30% of the enterprises belonged to the MSME sector. Whereas, the bottom 10th percentile of enterprises was dominated by MSMEs, representing 80% of the enterprises in the group. These enterprises also consumed ~ 0.01% of total energy and had an average turnover of INR 2 crore.

In order to evaluate the existing PAT thresholds in terms of their coverage of energy consumption, number and type of enterprises, around 2 lakh factories reported in the ASI unit level data of FY15 have been considered. For sub-sectors like food & beverages, transport equipment and machinery, which does not fall under the PAT coverage, a threshold of 3000 TOE has been assumed. These sub-sectors also have very small energy consumption footprint within the manufacturing sector. Table 4 highlights the distribution in energy consumption, number, and type for the enterprises that fall under the present PAT thresholds.

Sector	**Energy consumption (MTOE)**	**Energy share in sector**	**Energy share in sub-sector**	**Share of MSME units**	**Avg. Turnover (INR crore)**
Chemicals	4.27	0.42%	55.54%	0.00%	3098
Fertilisers	4.44	3.10%	95.66%	0.00%	2914
Food Processing, Beverages and Tobacco	2.40	2.19%	50.20%	62.32%	764
Iron & Steel	47.12	5.14%	89.94%	21.62%	1850
Machinery	0.62	0.66%	30.69%	58.67%	2099
Non-Ferrous Metals	13.38	2.75%	97.72%	55.63%	3602
Non-Metallic Minerals	15.16	0.81%	74.21%	21.97%	900
Pulp, Paper and Print	2.29	0.61%	65.44%	1.99%	1122
Textile and Leather	5.43	5.57%	70.59%	47.62%	384
Transport Equipment	0.67	2.67%	43.25%	27.23%	3455
Wood and wood products	0.04	0.44%	34.50%	32.54%	200
Non-specified Industry	0.97	1.92%	46.90%	32.54%	1078
All sectors	96.78	2.03%	80.29%	66.67%	1185

Table 4: Distribution of energy, number and type for enterprises under the existing PAT thresholds

With an annual energy consumption of 96.78 MTOE, these enterprises represented 80% of the manufacturing sector's energy consumption but, only 2% in terms of number of operational enterprises. While sectors like chemicals & fertilisers and pulp & paper have very low share of MSME units, the food & beverages, machinery, and non-ferrous sectors have the highest share of MSME units. However, except for food & beverages, the above-mentioned sub-sectors have very similar average turnover values. The proposed definition of MSME based on annual turnovers, will re-classify certain MSMEs to large enterprises especially for the transport equipment, machinery, and non-ferrous metals sub-sectors.

The DCs covered under the existing PAT scheme represents a total energy consumption of 87 MTOE compared to the 96.78 MTOE identified in Table 4 (BEE, 2016). The difference in coverage can be attributed to the iron & steel, non-ferrous metals, and textile sub-sectors where PAT DC's represent 86%, 79%, and 27% of their respective sub-sectors identified from the ASI database. Also, food and beverages, transport equipment, and machinery sub-sectors were not covered by the present PAT scheme.

The existing distribution of energy consumption in the manufacturing sector is the major barrier towards extending the coverage of PAT scheme. Reducing the thresholds to include smaller enterprises would lead to substantial increase in transaction cost with marginal increase energy savings. We have attempted to identify the feasible reduction levels of the existing PAT scheme by comparing the ratio of incremental of coverage of energy consumption to the number enterprises for every percentage decrease in the thresholds. This ratio is termed as *return potential*, reflecting the change in transaction costs with decreasing threshold levels. Figure 6 illustrates the impact from reduction of existing PAT thresholds on the return potential across the sub-sector levels.

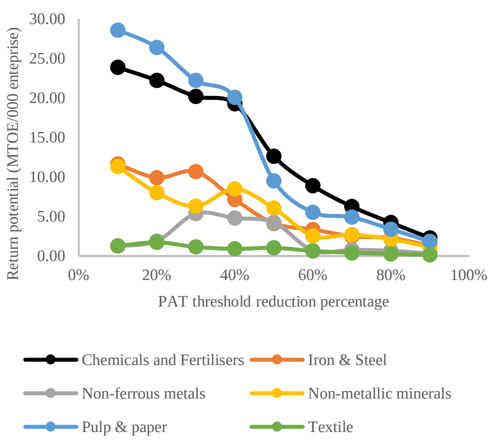

Figure 6: Sensitivity analysis of existing thresholds on return potential of the PAT scheme

The chemicals & fertilisers and pulp & paper industries indicated the highest return potential amongst the other sub-sectors. The return potential in these industries experiences a sharp drop when their existing thresholds are decreased by more than 40%. In the iron & steel sub-sector, a drop in the return potential is seen for threshold reduction beyond 30%. In the non-metallic minerals sector, the return potential peaks at 40% reduction of the existing threshold with continual decrease thereafter. The non-ferrous metals sub-sector shows the highest possible reduction of the existing threshold, the return potential for the sector decreases beyond 50% reduction of the threshold. The textile sub-sector has the lowest return potential, which also remains invariant with decreasing thresholds. One can plausibly attribute it to the large share of MSMEs operational in the sector.

CONCLUSION

The decomposition analysis indicated that the PAT period experienced a marginal decrease in energy consumption owing to the decrease in industrial output coupled with improvement in the energy efficiency levels. Although, the energy efficiency reduction was much larger in the PAT period compared to the pre-PAT period, the reduction was not observed across all the manufacturing sub-sectors. The reduction in energy efficiency was primarily driven by the iron & steel and non-ferrous metals sub-sectors. While chemicals & fertilizer sub-sector indicated a significant increase in energy intensity of production in-spite of the sub-sector being covered under the PAT scheme.

A closer look at the sub-sector indicated that designated consumers covered by the scheme represented ~ 60% of the overall energy consumed by the sub-sector. Reducing the existing PAT thresholds to cover the remaining industries, would significantly increase the transaction cost, while lead to marginal increase in energy savings. Based on the return potential, majority of the sectors had the reduction range between 30 – 40% of the existing PAT thresholds. However, the actual reduction potential would also depend on factors like future production outlook, current levels of energy intensity compared to best practices etc. Nevertheless, incremental measures like energy efficiency improvements would not be sufficient to meet the limit the temperate rise to under 2°C by 2100.

Globally, if the energy intensive sectors like iron & steel, cement, ammonia, and petrochemicals are assumed to achieve the best-in-class energy efficiency levels within the next 10 years, the cumulative emissions from these sectors would still consume ~

13% of the total carbon budget required to limit the temperature increase to 2°C by 2100, against ~ 15% in the BAU scenario (Biswas, et al., 2019).

The manufacturing sector's energy mix is heavily dominated by coal – catering to 78% of energy demand by the sector. The increasing reliance on coal for energy intensive industries like iron & steel, has offset the energy efficiency gains from PAT. Hence, despite overachieving the stated energy efficiency targets in PAT, there has only been a marginal impact on emissions levels itself. Thus, highlighting a need for policy actions that look beyond the incremental process efficiency gains and aim for deep decarbonization of industrial energy use.

NOMENCLATURE

E = Total energy consumption (All sectors)

Q = Overall activity level of the manufacturing sector (expressed in production output)

E_i = Energy consumption of the i^{th} sector

Q_i = Activity of i^{th} sector (expressed in production output)

S_i = Activity share of i^{th} sector

I_i = energy intensity of i^{th} sector (expressed as energy consumption per unit production)

C = Overall emissions from the manufacturing industry

C_{ij} = Emissions from i^{th} industry due to j^{th} fuel use

E_{ij} = Energy consumption of the i^{th} sector by j^{th} fuel

M_{ij} = Energy consumption share from j^{th} fuel in i^{th} industry

U_{ij} = carbon emission factor of j^{th} fuel in i^{th} industry

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ANNEXURES

Manufacturing Sector	**2-digit NIC 2008**	**2-digit NIC 2004**
Chemicals & fertilisers	20, 21	24
Food Processing, Beverages and Tobacco	10, 11, 12	15, 16
Iron and Steel	24	27
Machinery	25, 26, 27, 28, 30	28, 29, 30, 31, 32
Non-Ferrous Metals	24	27
Non-Metallic Minerals	23	26
Non-specified Industry	22, 26, 31, 32, 72	12, 25, 33, 36
Pulp, Paper and Print	17, 18	21, 22
Textile and Leather	13, 14, 15	17, 18. 19
Transport Equipment	29, 30	34, 35
Wood and wood products	16	20

Annexure 1: Industry sectors used in analysis with their NIC codes

Manufacturing Sector	**2004-05**	**2011-12**	**2012-13**	**2014-15**
Chemicals & fertilisers	106057	206555	206153	205362
Food Processing, Beverages and Tobacco	78478	149735	147840	152273
Iron and Steel	122809	184986	172362	187024
Machinery	81640	197209	188056	167303
Non-Ferrous Metals	40866	44815	45839	46100
Non-Metallic Minerals	38337	63219	62278	60454
Non-specified Industry	38718	90076	88585	92051
Pulp, Paper and Print	12865	21582	21710	23305
Textile and Leather	62280	102850	106634	120950
Transport Equipment	108190	227769	208495	224219
Wood and wood products	802	1873	2129	1939

Annexure 2: Sector-wise Production Output (in INR crores)

Manufacturing Sector	**2004-05**	**2011-12**	**2012-13**	**2014-15**
Chemicals & fertilisers	3.94	2.69	3.49	5.94
Food Processing, Beverages and Tobacco	1.57	1.07	1.00	1.01
Iron and Steel	16.85	16.03	20.79	18.30
Machinery	1.02	0.54	0.51	0.37
Non-Ferrous Metals	11.24	17.74	17.96	10.21
Non-Metallic Minerals	22.36	18.71	19.19	20.12
Non-specified Industry	0.66	0.66	0.98	0.69
Pulp, Paper and Print	15.21	9.98	10.37	10.81
Textile and Leather	3.17	2.78	3.06	2.77
Transport Equipment	0.39	0.34	0.46	0.32
Wood and wood products	2.49	1.56	1.60	1.24

Annexure 3: Sector-wise Energy Intensity of Production Output (in TOE/Million INR)

M&V IN ESPC: THE U.S. FEDERAL EXPERIENCE AND IMPLICATIONS FOR DEVELOPING ESPC MARKETS

Philip Coleman[1], Shankar Earni[1], Bob Slattery[2], Christine Walker[2]

[1]*Building Technologies & Urban Systems Division*
Lawrence Berkeley National Laboratory
Berkeley, California, United States
PEColeman@lbl.gov
SEarni@lbl.gov

[2]*Energy & Transportation Sciences Division*
Oak Ridge National Laboratory
Oak Ridge, Tennessee, United States
SlatteryRS@ornl.gov
WalkerCE@ornl.gov

ABSTRACT

The United States Federal Government has been conducting guaranteed savings energy savings performance contracts for over 20 years and now relies on ESPC for the majority of its energy efficiency work. Along with a related financed project type, these deals resulted in $4.2 billion of project investment in the five years ending in 2016, a pace that has even accelerated since.

Measurement and verification (M&V) on the projects is the key to assuring savings realization and persistence. Perceived as a weakness or burdensome added cost in the early years of the program, M&V has become a strength. All energy conservation measures (ECMs) have some form of measurement – defined as a measured baseline establishment followed by at least one measurement of the main energy-saving parameter taken in the performance period for each ECM. The government's in-house energy consulting office, the Federal Energy Management Program (FEMP), now recommends measurement of these "Option A" M&V ECMs throughout the contract term, usually annually. Moreover, a significantly higher percentage of projects are now characterized by more ambitious M&V, including Option B (all parameter measurement) for most generation (including renewable) and some efficiency measures, and more frequent Option C (whole facility utility bill analysis) for "deep retrofit" projects with multiple, interactive ECMs. Coincident with this progress in M&V has been a much greater embracing of ESPC by the federal agencies, resulting in the enormous rate of projects now executed.

This paper traces the evolution of M&V in federal ESPC and argues that the heightened credibility of the savings has contributed significantly to the procurement vehicle's long-term viability. This focus on savings integrity via M&V has been learned over two decades for U.S. federal ESPC, but countries with developing ESPC markets would be wise to emphasize it as their markets emerge, allowing them to avoid some of the "growing pains" experienced in the U.S.

***Keywords*—**energy savings performance contracting (ESPC or EPC), energy service companies (ESCOs), measurement and verification (M&V)

ESPC'S HISTORY IN THE U.S.

Energy savings performance contracting (ESPC) has a now 40-year history in the United States. Not surprisingly, it has evolved considerably. The ESPCs of the late 1970s and early 1980s were conducted using "shared savings" approaches, in which the energy service company (ESCO) would generally borrow the money and install energy conservation measures (ECMs) at a facility for no up-front cost. The ESCO would then be paid a proportion of the energy bill savings that ensued over the years of the contract (with the customer retaining the other portion). Shared savings is a simple and intuitively desirable business model, but it had two key flaws that became exposed over time. The first is that it involves a transfer of energy price risk from the customer to the ESCO for the energy being saved in a deal. This meant that once energy prices fell – as they did in the U.S. in the late 1980s – many of the deals fell short of their expected savings, jeopardizing not only the ESCOs' returns but their credit (Hansen, 2009).

A second problem with the shared savings model is more nuanced. Since the energy bill was the ultimate arbiter of the savings achieved, the units of energy saved (along with their price) was what ESCOs were relying on to make their returns. This is ostensibly very sensible, because it put the performance risk on the ESCOs' shoulders. However, it also saddled those same ESCOs with the risk that their customers might add floor space, hours, employees, or customers (think of hotels, for instance), or produce more of their product, all of which tend to drive up energy usage. At its core, the associated challenge is one of measurement and verification (M&V) of the savings: how it's conducted (e.g., via the bill or in some other manner), how to account for changes at the facility outside of the ESCO's control, and, at the broadest level, how risk is divided between the customer and ESCO. Though the term had not yet been coined, these pioneering shared savings ESPC projects were employing "Option C" M&V – also known as utility bill analysis. Option C (one of four key options that are described below) is the most intuitive of M&V methods: compare the whole facility consumption before and after the intervention.

While Option C M&V often includes provisions for weather adjustments (usually based on regression analysis with heating or cooling degree days), there are a lot of other factors that can affect utility bills and they are generally difficult to account for because they may not have occurred before at the facility (consider staffing increases or space additions, for instance). This deems the magnitude of their future impact difficult to gauge. Moreover, it is also the case that ESCO-installed equipment might not be operated and maintained properly by the customer. For these reasons, these early ESPCs resulted not uncommonly in conflict (including lawsuits) between ESCOs and their customers (Hansen, 2009; Shonder and Avina, 2016).

EMERGENCE OF FORMAL M&V AND GUARANTEED SAVINGS

To help resolve this problem and generally regain credibility for the industry, two key changes ensued. The first was the mid-1990s development, primarily supported by the U.S. Department of Energy, of an objective guideline for how to conduct M&V. This effort, originally dubbed the North American Measurement and Verification Protocol (NEMVP) and later re-named the International Measurement and Verification Protocol (IPMVP), outlined four "options" – Options A, B, C, and D – by which ECMs could be measured and their savings verified. The first two (A and B) involve a "retrofit isolation" approach, in which the ECM's effects are measured in isolation, divorced from other impacts in the facility (e.g., portable power meters are used to gauge the power draw from the lights before and after the lighting change-out, and light loggers measure the hours of operation before and after the vacancy sensors' installation). Option A involves measurement of just the "key" parameter, whereas Option B directs measurement of all relevant parameters (sometimes involving a dedicated meter). Retrofit isolation can be a very effective way to measure savings, especially when an ECM's effects are not complex nor highly interactive with other ECMs.

A second important change in the industry was the move away from the shared savings model and toward a new concept called "guaranteed savings," in which the ESCO would commit to its performance – i.e., delivering a given amount of energy savings – but leave the energy price risk with the customer. Expected or conservative energy pricing was projected and included in the deals, but only to demonstrate that the guaranteed energy savings would translate into sufficient money savings to cover the payments on the financing. The latter was more and more commonly arranged by the (usually public sector) customer, rather than the ESCO, in various forms including direct loans but also general obligation bonds and various lease arrangements with the ESCO or equipment supplier (Hansen, 2009).

Together with the rise of the guaranteed savings model came a shifting reliance in M&V on Options A (retrofit isolation, with the key parameter measured) for simpler ECMs and, for more complex ones, Option D, which involves a computer simulation of the affected building(s), with and without the retrofits installed (Shonder and Avina, 2016). These M&V methods largely insulate ESCOs from factors like space additions, occupancy changes, O&M negligence, or even just unspecified "load creep." This is particularly the case when the post-installation savings measurements are made only once, just prior to project acceptance, and then stipulated as constant for the remainder of the term, as was often the case (Shonder and Avina, 2016). While this shift was in one sense a plus for the industry, ridding ESCOs of risk for variables they did not control, it also served to distance these ESPCs from the appeal of the original shared-savings model, in which the utility bill (even leaving out unit prices for energy) was the determinant of the project's performance. Utility bills come from largely dependable and disinterested third parties to the deal, not to mention their expression in currency, rather than more esoteric energy units like kWh and Btus. This understandably makes them easier to grasp, particularly for non-engineers engaged in the ESPC negotiations.

Consequently, the new generation of ESPCs, using guaranteed savings and limited M&V, and largely insulating ESCOs from performance (not to mention price) risk, lost some of their original appeal (Shonder and Avina, 2016). One testament to this is that even today (2019), many customers still insist on Option C M&V, even though virtually all ESPCs in the U.S. are now guaranteed savings deals. On the other hand, customers in the non-federal market have increasingly taken to terminating their performance period deals with their ESCOs after two to five years, citing their confidence that the savings are being achieved or – consistent with the thesis that the absence of measurements during the performance period deemed the M&V less worthwhile – that they did not see sufficient value in the ongoing M&V (Gilligan, 2017).

ESPC IN THE U.S. FEDERAL GOVERNMENT

Guaranteed savings ESPCs were authorized for U.S. federal government facilities with the passage of the Energy Policy Act of 1992, and started gaining momentum in the government following a subsequent (1995) DOE rule and the creation in 1998 of "indefinite delivery, indefinite quantity" (IDIQ) contracts by the Department of Energy and the U.S. Army Corps of Engineers. The number and dollar volume of the projects have vacillated over the years, but have reached unprecedented levels in the last four years (2016 to 2019), with nearly a billion dollars of investment annually by ESCOs working in the federal sector.[1]

While use of ESPCs was permanently authorized in 2007 (prior authorizations had been only temporary), use of the vehicles was inconsistent both across and even within federal agencies, with some agencies at times turning away from them altogether for a matter of years. Project volume started accelerating in 2012, with $4.2 billion being executed in the five-year span between 2012 and 2016, the period of a "Presidential Performance Contracting Challenge" (PPCC) from President Obama. But even in the absence of a similar push from the Trump administration, the high volume from the PPCC has continued in the last three years. And of the six agencies who have made the most use of ESPCs, all have been very active over the last three years for which complete data are available (2016-2018), with between 7 and 33 awarded projects and between roughly a quarter and a half billion dollars of project investment per agency (over the three-year span). In contrast, over the 21 years since the inception of the IDIQs, four of those six agencies had at least one three-year period in which they awarded either zero (three of the four agencies) or one project per year (the fourth agency).

What explains this seeming souring – or at minimum, loss of interest – toward ESPC by these agencies and their subsequent return to active use of the vehicle? There are several factors, from agency procurement policies that made use of ESPCs unattractive for eligible ESCOs to concerns about ESCO pricing of the deals. However, in interviews with long-time ESPC leaders at the four agencies that had the long hiatuses from ESPC, two brought up concerns about M&V and the legitimacy of the savings guarantees in explaining why his or her agency had ceased, or nearly ceased, its ESPC activity for years at a time.

In contrast, each of these representatives also shared that their agency, in resuming ESPC activity, put an increased emphasis on M&V and savings integrity. For instance, one of the agencies now requires that 70% of the savings in its ESPCs use metered M&V, i.e., IPMVP Options B (retrofit isolation, all parameter measurement) or C (whole facility utility bill analysis) (Allison, 2018). Another strongly pushes the ESCOs working with it to adhere to a set of recommended M&V outlines (originally developed for the agency itself and now incorporated by DOE's Federal Energy Management Program, FEMP, in its M&V guideline document) covering 19 of the most popular ECMs (Spader, 2019). Perhaps not coincidentally, all of these agencies have transitioned their ESPC activities to a single, central office commissioned by headquarters, rather than having the individual projects led by personnel at the customer sites themselves.

INCREASED M&V RIGOR VIA FEMP GUIDELINES

Concurrent with individual federal agencies' push for more rigorous M&V has been a tightening of the government's recommended M&V practices, as authored by FEMP. FEMP first published its guidelines in 1996, just after the 1995 publication of DOE's rule on ESPC and shortly before the signing of its first indefinite delivery, indefinite quantity (IDIQ) contracts with ESCOs in 1998. The document was updated in 2000 as *M&V Guidelines: Measurement and Verification for Federal Energy Projects (Version*

[1] See, for instance, the annual list of projects under DOE's IDIQ at https://www.energy.gov/eere/femp/downloads/doe-idiq-energy-savings-performance-contract-awarded-projects.

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2.2). Version 2.2 stated explicitly that it was an "application of the IPMVP to federal projects." Nonetheless, in contrast to the contemporaneous version of the IPMVP, Version 2.2 permitted "stipulation" of all savings variables – i.e., it required *no* measurement whatsoever – for its rendition of Option A for three common ECMs: chillers, lighting, and water conservation from retrofitted plumbing fixtures.

Versions 3.0 (2008) and 4.0 (2015) of the guidelines made Option A M&V progressively more rigorous. Version 3 dispensed with allowing "pure stipulation," requiring – consistent with the IPMVP – that all Option A M&V always include both pre- and post-retrofit measurement of an ECM's key parameter. Version 4 took that a step further, making the default condition that measurement of the key parameter occur *annually* during the performance period, as opposed to the common practice of just one or two measurements (the first, and often only, one taking place during the post-installation inspection). Exceptions are permitted, especially for simple and reliable ECMs like one-for-one lighting retrofits.

In addition to fortifying Option A, Version 4 made a couple of other significant strides towards improving rigor. One small step involved Option C, which has not been widely used in federal ESPC traditionally. Version 4 made clear that an obstacle to the use of Option C, one that is prominent in the eyes of ESCOs, is that facilities' use profiles – including their occupancy, hours of operation, activities (think of office space that becomes an exercise center), plug loads, etc. – almost inevitably changes over time, sometimes substantially. Consequently, ESPCs that use Option C in these buildings subject their ESCOs to risks that the ESCOs generally have no control over. Version 4 emphasizes that where Option C is used – and it is sometimes a very defensible choice when multiple interactive ECMs are being deployed, and savings are high – it may make sense to use Option C only in the first two or three years of performance, after which a switch to different options (generally the retrofit isolation options, A and B) is a sensible approach. In other words, prove to us that the very large savings are being achieved, after which we understand that our facility "noise" may obfuscate things and we'll accept "lesser" (retrofit-specific) proof that guaranteed performance is being achieved.

The most conspicuous difference between Version 4 and its predecessors was the unprecedented move to include a new section of the guidelines that identifies, for 19 common ECMs, what its authors consider to be good practice M&V. A whole chapter is devoted to providing short (one- to two-page) outlines of recommended M&V plans, each associated with a specific IPMVP option (i.e., A, B, C, or D). This may not seem monumental, but it was unprecedented for either the FEMP guidelines to be anything other than agnostic about M&V option choice. FEMP now routinely trains federal audiences to query their ESCOs in instances where the recommended options (and associated plans) are not being employed for ECMs that are covered by the guidelines' plan outlines.

TREND AWAY FROM OPTION A AND TOWARDS METERED M&V (OPTIONS B AND C)

Consistent with the aforementioned effort by the agencies to inject greater rigor into their ESPCs' M&V have been programmatic M&V trends over the two decades. FEMP has tracked the M&V used for all ECMs under ESPC projects using its IDIQ[2]. The results, tabulated both in terms of the frequency and dollar volume of options employed, support the thesis of increasing rigor.

The most telling contrasts are from the first ten years of awards (1999-2008) compared with the most recent four (2016-2019), i.e., the period subsequent to the release of Version 4.0 of FEMP's M&V guidelines. Per Figure 1, the proportions of ECMs, as well as dollar investment, using Option A has declined considerably, from 75.1% of ECMs representing 70.2% of project investment in the first decade of the program to 64.2% of ECMs and just 46.2% of investment in the 2016-2019[3] span. Compensating for this decline, ECMs using Options B and C were just 18.2% of the total count, representing 22.9% of investment in the 1999-2008 period. In contrast,

[2] What FEMP tracks is the "first year" M&V, i.e., the M&V option employed in the first year of performance following acceptance. There are instances when the initial M&V transitions (usually to a less rigorous option, e.g., from C to A) after the first two or three years of project performance.

[3] The 2019 numbers presented here extend only through mid-September, 2019 because of the timing of this manuscript.

34.7% of ECMs and a majority 52.5% of project investment utilized Options B and C from 2016 to 2019.

Table 1. ECMs' use of Option A versus Options B and C – early years and recent history.

Per-iod	Option A (#)	Option A ($)	Option B/C (#)	Option B/C ($)
1999 - 2008	528/703 (**75.1%**)	$94.1M (**70.2%**)	128/703 (**18.2%**)	$22.0M (**22.9%**)
2016 - 2019	233/363 (**64.2%**)	$70.9M (**46.2%**)	126/363 (**34.7%**)	$80.6M (**52.5%**)

This trend underscores the gravitation towards greater rigor that the agencies appeared to be pursuing, echoing the interview comments from several of the major ESPC users. It is particularly noteworthy in light of the fact that, as mentioned above, FEMP's application guidance for these projects actually made Option A notably *more* rigorous in 2008 and then further again in 2015.

While the greater rigor is indirectly reflected in the agencies' greater confidence (i.e., higher investment) in ESPCs, it can also be seen more directly in progressively increasing reports of achieved savings from the deals. The most recent results from active projects using FEMP's IDIQ, of which there were 185, report savings realization at 108% (105% considering "government impacts" to savings) of the guarantees (Walker, 2019). While these are ESCO-reported figures, the fact that the percentage is at a 21-year programmatic high amidst progressively tighter M&V (not to mention increasing emphasis on agencies "witnessing" the ESCOs' M&V activities) is telling.

CONCLUSION

In two decades of doing guaranteed savings ESPCs, the U.S. federal government has learned a great deal; the market and its customers have matured. One key facet of that learning has revolved around the way M&V is executed for federal projects. Where rigor was questionable, both as enforced by the customer agencies and also codified by FEMP (their in-house consultant for ESPC), it has evolved. This is evident in the tightening of the government's own guidelines for M&V – in the form of FEMP's setting a progressively higher bar for the minimum acceptable form of M&V (Option A), as well as in providing recommended options and skeleton plans for different ECMs. The evolution is also apparent in the agencies' trend away from reliance on Option A (its increased rigor notwithstanding) over time. Lastly, those same agencies stated commitments to strive for greater savings integrity in their projects, while merely anecdotal, is reinforced by their obviously increased faith in ESPC as an energy savings (and infrastructure renewal) tool: federal ESPC volume is at an unprecedented level of nearly a billion dollars of investment per year, and all six of the agencies who have used ESPC most actively over the past two decades are now tapping it at higher rates than ever before.

So what does the U.S. government's ESPC experience have to offer to other entities (including countries) pursuing ESPC programs? There are numerous lessons learned. Some – like the advantages of developing central centers of expertise to execute the deals, rather than training individual site teams one after another – don't necessarily, or at least primarily, have to do with M&V. However, several key lessons very much revolve around M&V. All of them can be distilled down to one key point: push for savings integrity, both in individual deals and the policy guidance that underlies them. While the cost of M&V is legitimately viewed as parasitic on the deals, since it costs money and doesn't offer additional savings, *per se*, this cost (which in the U.S. federal program averages less than 3% per year of the projects' savings) seems trivial when viewed in light of the confidence it appears to confer:. Where in the first decade or so of their availability, agencies' use of the vehicles was marked by start-and-stop intervals, the recent pattern has been sustained very high ESPC investment. The central theme underlying this heavy reliance on the projects is obvious: confidence in these vehicles' meeting their expectations – particularly regarding their realization and persistence of savings – is essential to their enduring use.

ESPC is a very powerful tool, with enormous potential for achieving energy savings, due to its appealing public-private partnership aspect and "paid from savings" financing. Countries with emerging ESPC markets would be wise to heed the lessons learned from those with more mature markets. The importance of savings integrity in ESPCs – particularly, the belief that the projects are performing as claimed (i.e., generating and maintaining their savings) – is crucial to customers sustained use of the vehicle.

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MARKET TRANSFORMATION TOWARD ENERGY EFFICIENCY IN INDIAN MSMES THROUGH INNOVATIVE BUSINESS MODELS AND BULK PROCUREMENT

Mrinal Saurabh Bhaskar[1], Soumya Prasad Garnaik[2]

[1]*Energy Efficiency Services Limited*
New Delhi, India
mrinalsbhaskar@gmail.com

[2]*Energy Efficiency Services Limited*
New Delhi, India
spgarnaik@eesl.co.in

ABSTRACT

Micro Small and Medium Enterprises (MSME) sector in India is one of the major contributors in India's Gross Domestic Product (GDP). With around 63.4 million units across India, MSME sector is contributing 33.4 % of India's manufacturing output. A significant portion of these units are energy intensive and the energy cost of these units contributes 30-40% of their production cost. Majority of the MSME units are still using old technologies and inefficient operational practices which results them to pay more towards energy cost and also contributes to the Green House Gas (GHG) emissions. Studies shows that the major challenges faced by MSME in adoption of energy efficiency is lack of knowledge, not confident on technologies, lack of finance and unavailability of local service provider. To address these challenges and to create market transformation for energy efficiency in MSME sector, Global Environment facility (GEF) and several donors/partners[1] are funding a new initiative that will be implemented by the Super ESCO EESL. This program aims to identify energy efficient technologies in the MSME clusters which has significant energy saving and replication potential. EESL will do demonstration of the identified technologies with innovation business model with pre and post measurement of the new technology. Once the proof of concept is established, EESL will do bulk procurement of the technologies which shall reduce the price of the technology and make it more affordable.The total duration of the project is of 36 months.
In this paper, details of the project, its innovative business model, market potential and a successful case study will be explained.

Keywords— MSME, energy efficiency, ESCO, business model, revolving fund, cluster

INTRODUCTION

Micro Small and Medium Enterprises (MSME) sector in India is one of the major contributors in India's Gross Domestic Product (GDP). With around 63.4 million units across India, MSME sector is contributing 33.4 % of India's manufacturing output. Over the past few decades, the Micro, Small and Medium Enterprises (MSMEs) sector has emerged as one of the most dynamic sectors in the Indian economy. Out of the total number of MSMEs in India, around 31%[2] is of the manufacturing sector which is highly energy intensive and also generating around 36 million jobs in India. Although, MSME sector in India is functioning for the last six decades within a protective industrial and economic framework, a large section of MSMEs remains isolated from modern technological developments. These MSMEs are still using obsolete and inefficient technologies to utilize commercial energy sources, leading to wastage of energy, as well as the release of high volumes of greenhouse gases which are harmful to health and damage the atmosphere. Government of India along with other bilateral and multilateral agencies have

[1] United Nation Industrial Development Organization (UNIDO); Ministry of MSME; Bureau of Energy Efficiency (BEE); Small Industrial Development Bank of India (SIDBI); Ministry of enviornment Forest and Climate Change (MoEFCC) and Energy Efficiency Services Limited (EESL)
[2] MSME annual report 2018-19

implemented various interventions for accelerating the energy efficiency and technology up-gradation of the MSME units. However, the energy efficiency transformation pace has been observed as sluggish. The key barriers identified for the slow pace of adoptions are: a) High cost of new technologies b) lack of effective financing mechanism c) Risk for technology failure d) Lack of awareness and knowledge towards new technologies e) Unavailability of local service providers etc.

ABOUT THE PROGRAM

To address the barriers in adoption of efficient technologies by MSMEs and to transform the Market for Energy Efficiency in MSMEs, Global Environment facility (GEF) along with United Nations Industrial Development Organisation (UNIDO), Ministry of MSME and Energy efficiency services limited (EESL) launched a program namely "Promoting Market Transformation for Energy Efficiency in Micro Small and Medium Enterprises (MSMEs)". Bureau of Energy Efficiency (BEE) and Small Industrial bank of India (SIDBI) are also key partners in this program which is under the fifth GEF funding cycle. The program duration is of 36 months and the objectives of the program are:

- To promote the implementation of energy efficiency in the MSME sector
- To create and sustain a revolving fund mechanism to ensure replication of energy efficiency measures in the sector;
- To address the identified barriers for scaling-up energy efficiency measures and consequently promote a cleaner and more competitive MSME industry in India.

To meet the objective, following components of the program have been identified.

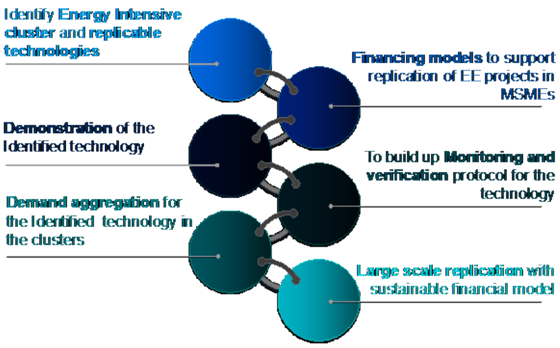

Figure 1: Program Components

Under this program, **10** energy intensive MSME clusters have been identified and **35** energy efficient technologies will be identified in these clusters which have high replication potential in the cluster. Once the technologies are identified, the demonstration of these identified technologies will be carried out in the **70** identified MSME units (2 unit per technology) as a **proof of concept**. The demonstration would not only cover the technology but also the business model. Once the demonstration is completed successfully, large scale replication of the technology will be undertaken by EESL through demand aggregation. The large scale replication shall ensure the drop in technology price, more competition in the vendor market, establishment of local service center for vendors and support ESCO (Energy Service Companies) to invest in selected technologies. One of the key components in this program is of creation of *EESL MSME Revolving Fund (EMRF)*. This fund will be created to support the implementation of the technologies in the MSME cluster after the completion of this program. The repayment by the MSME owners for the implemented technologies will be made in the EMRF account.

METHODOLOGY

The program adopts a very consultative and transparent approach to meet the objectives. To take the key decision in the scheme, a high-level technical committee namely Project Steering Committee (PSC) has been formed which comprised members from Ministry of MSME, Bureau of Energy Efficiency (BEE), Ministry of Environment Forest and Climate Change (MoEFCC), UNIDO, EESL and SIDBI. This committee is responsible for making key decisions on the finalisation of technologies, business models, repayment structures, etc. A sub-committee namely Working Technical Group (WTG) have also been formed to evaluate the technologies and its business model for endorsement to the PSC. WTG comprises members who have rich experience in Industry, technologies, policies, finance, ESCO market, etc.

Selection of Clusters:

EESL selected cluster based on the criteria shown below.

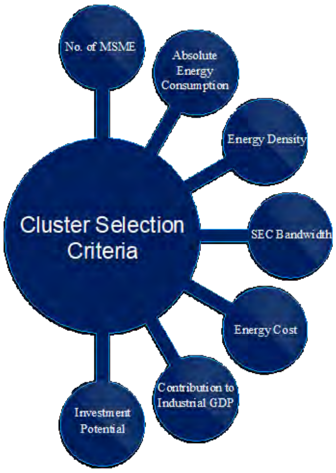

Figure 2: Criteria for cluster selection

EESL have done some secondary research, visited few clusters, interacted few government agencies, reviewed some reports to arrive at the date on above criteria for various clusters. The PSC then shortlisted following 10 clusters for this project.

NAME OF CLUSTER	STATE	SECTOR
Surat	Gujarat	Textile
Ankleshwar	Gujarat	Chemical
Jorhat	Assam	Tea
Howrah	West Bengal	Mix
Varanasi	Uttar Pradesh	Textile
Muzaffarnagar	Uttar Pradesh	Paper
Batala, Jalandhar & Ludhiana	Punjab	Foundry
Vellore	Tamil nadu	Rice Mill
Sundargarh	Odisha	Sponge Iron
East & West Godavari	Andhra Pradesh	Ceramic

Table 1:List of identified clusters

Selection of Technologies:

Upon finalisation of the cluster, EESL started interacting with Industry association and MSME units to explain the project and conducted meetings, workshops and surveys in the cluster. EESL collected signed survey forms from minimum of 100 MSME units per clusters. Based on the outcomes of the survey, interaction with MSME units and associations, EESL conducted detailed energy audit in selected MSME units to identify the potential technologies, its parameters, energy saving potentials, etc. 3-5 technologies will be selected in each cluster to meet the total target of 33-35 technologies. The selected technologies will then be presented to WTG and PSC for approval. The technologies will be evaluated based on the following 5 criteria.

Figure 3: Technology selection criteria

Based on the above 5 criteria, the committee approves the identified technologies to be implemented in the cluster. As of now, the committee have approved 13 technologies to be implemented in 6 of the clusters.

Demonstration of Technologies:

Once the technologies are approved by PSC, 2 units for each technology will be selected on a first come first serve basis. A baseline energy audit shall be conducted in the identified demonstration (DEMO) units to establish the baseline and the technical parameters. After the baseline results, meeting with various vendors would be conducted to understand the capabilities of the vendor, explain to them about the project and discuss the technical aspects of the technologies. EESL addresses the queries and suggestion if deemed fit and procure the technologies for the DEMO units through an open tendering process. However, to ensure the participation of the DEMO unit in the project, EESL signs an agreement with the DEMO unit and collects advance payment from the unit as part of the business model. Once the vendor is selected through an open tendering process, the installation process initiates at the Demo unit which may require some civil works as well. After the installation is done, EESL conducts Measurement and Verification (M&V) for the agreed duration of time with the help of suitable instrument. The M&V would be carried out by an independent agency in the presence of EESL and MSME unit. When the savings are established, the repayment process will be initiated by the MSME unit to EESL.

Business Model:

To implement the technology in the MSME unit, EESL adopts a very simple yet innovative business model. Under this business model, EESL provides two options for the MSME units. In the 1st option, 80% of the project cost will be borne by EESL and MSME unit have to do upfront invest to the tune of 20% of the project cost. The 80% investment made by EESL for DEMO of technologies will be free of interest. MSME units need to repay EESL's share in an easy quarterly installment from the energy savings they will be achieved from the technology implementation. In the second option, the MSME unit may invest 100% of the project cost as an upfront payment to EESL and rest all will remains the same. MSME unit need not pay anything extra during the project period. A simple illustration of the business model is as shown below.

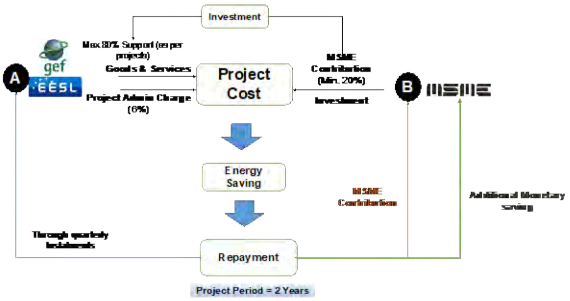

***Figure 4: Business Model*[3]**

To ensure the security of the payment, EESL has defined a payment security mechanism which will be in the form of either Bank guarantee or Escrow account or Post Dated Cheque. The benefit of this business model is that MSME units need to pay only 20% of the total project cost and the rest amount, they have to pay from the energy savings through quarterly EMIs. To address the difficulties in the technology operations, all the technologies procured by EESL would be having extended warranty and annual maintenance contract (AMC) for about 3 years. The cost towards AMC and extended warrantee will be included in the final price of the technology. Technology suppliers need to resolve the issue within the specified time.

DISCUSSION AND RESULT ANALYSIS

For Surat textile cluster, EESL has identified 5 technologies namely:

- Variable Frequency Drive (VFD) based Screw compressor with minimum IE3 motor
- Programmable Logic Control (PLC) based automation system in Jet dyeing machine
- Online combustion efficiency monitoring and control system
- Condensate and flash steam recovery system
- Micro turbine system

Out of the five identified technologies, the result of Screw compressor and the business model will be explained here.

In the Surat Textile cluster, there are more than 300 MSME units which are doing textile processing. Based on the survey conducted, the majority of the units are still using Reciprocating compressors which are less efficient. Based on the energy audit and discussion with the vendors, through replacement of reciprocating air compressor with screw compressor (VFD and IE3 motor) an energy saving of around 10-15% is expected with a payback period of 1.5-2 years. EESL identified 2 DEMO units and conducted baseline energy audit in the units. The compressed air demand for these two units was around 240 and 88 cfm with average specific power consumption of around 0.29-0.32 kw.cfm. The total motor ratings of these two units varies from 27-60 kw. Based on the baseline audit results and discussion with vendors, EESL floated tender for procurement of VFD based Screw compressor with min IE 3 motor with extended warrantee and AMC for **3 years**. As expected, the final price of the technology discovered from bidding process was about **23%** less than the market price. The transportation and installation for the technology took around 1 month time. Post implementation and stabilisation, M&V was conducted for at the Screw compressor for multiple number of times to evaluate the energy savings. The measured SEC of both the compressors were minimum less than 40% from the baseline SEC. This has resulted in an annual energy saving of around USD 1400/month (Rs 1 lakhs per month). The details of the DEMO are as below.

PARAMETER	**VALUE**	
	DEMO 1	DEMO 2
Baseline specific energy consumption	0.29 kW/cfm	0.32 kW/cfm

[3] For some defined cases, EESL may invest 100% of the technology cost and MSME unit need not to pay any upfront amount.

Achieved specific energy saving	0.16 kW/cfm	0.17 kW/cfm
Saving (%)	44	46
Monetary saving/year	USD 6700 (Rs 4.8 lakh)	USD 20200 (Rs 14.5 lakh)
Simple payback period (months)	17	10

Table 2: Result of Demonstration with VFD based Screw Compressor in Surat Textile Cluster

This technology has the investment potential to the tune of about Rs. 20 Cr in Surat Cluster with electrical energy saving potential of about 11 million units which may result in a CO_2 emission reduction of about 9900 tonnes in the cluster. After successful implementation of Demo of technology and business model, EESL conducted workshops to showcase the energy saving and success of the program to create awareness in the cluster as a result of which the demand for implementation of this technology has increased. EESL is in process of bulk procurement of Screw compressor which is at the final stage of the bidding process.

CONCLUSIO

Considering the need to upgrade the energy benchmarking of the MSME sector in India, this program plays an important role not only to create awareness towards energy efficiency but to reduce the GHG emissions from these industries by adopting efficient technologies. This program will support around 500 MSMEs during the program tenure which shall result in an estimated energy saving of 110000 TOE and 1 million tonne of CO2 emission reduction with an investment potential of around 150 mn $. This huge investment potential can play a catalyst to the ESCO market in India and also to the technology suppliers. The EMRF would be functional after the program to support the MSME units to adopt efficient technologies. Ministry of MSME may club their other schemes with this program so that it will be easy for any MSME to get the benefits. Under this project, EESL has identified more than 15 energy efficient technologies which has huge potential for replication not only in identified cluster but PAN India. Overall, based on the results of the DEMO and response from the Industry associations and MSME units, this program has a huge potential for market transformation for adoption of energy efficient equipment and addressing the barriers of MSME in India.

ACKNOWLEDGEMENT

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THE ROLE OF INDUSTRY ASSOCIATIONS AND LOCAL SERVICE PROVIDERS IN CATALYSING ENERGY EFFICIENCY IN MSMEs

Koshy M Cherail[1], Bhaskar Natarajan[2],
Alliance for an Energy Efficient Economy, India
Koshy@aeee.in, Bhaskar@aeee.in
1. Presenter 2. Co-author

ABSTRACT

Significant work has been done by the Government of India through the line Ministries - Ministry of Power (MOP) and Ministry of Micro, Small and Medium Enterprises (MSME), and other related departments to energise the MSME sector to adopt new, energy-efficient and renewable technologies. The MSME sector has been the beneficiary of many Multi-lateral, Bilateral, and Foundations supported programmes. State Governments have provided subsidies and grants for power and to augment infrastructure and for marketing creation.

The success of these programmes have been enhanced by the local industry associations (IAs), cluster leaders, and proactive local service providers (LSP), and the Energy Management Cells (EMCs). There is limited documented reports on how these entities have worked together to create a favourable environment.

The paper covers two different approaches: (1) The GEF, UNIDO-BEE, DC-MSME and MNRE programme with the help of Case Studies on Thanghad Ceramic Cluster, Gujarat and its Association – the Federation of Ceramic Industries.

(2) Secondly, IAMSME (Integrated Association of Micro, Medium & Small Enterprises), which has emerged from the Faridabad Industries Association, Faridabad, Haryana. IAMSME facilitates the growth and development of small businesses across India, through its network of chapters. The IAMSME's programmes to promote EE has benefited several of the SME units.

IAMSME provides a wide range of technical, financial, legal and business advisory services to its Members, much more than what typical industry associations offer. Some of the services include credit facilitation, technology transfer, risk management, skills upgrading, Energy Efficiency, solar power, sustainability, lean manufacturing, best-practices sharing and IT-enabled services and solutions.

Keywords: Energy Efficiency, MSME Cluster Development, Industry Associations, Energy Efficiency Investment, Energy Efficient Technology Upgradations

INTRODUCTION

Significant work has been done by the Indian Central Government through the Line Ministries – the Ministry of Power (MOP), the Ministry of Micro, Small and Medium Enterprises (MSME), the Ministry of New and Renewable Energy (MNRE) and other related departments and organisations to catalyse the MSME sector to adopt new, energy efficient and renewable technologies and best practices. State Governments have also provided subsdies and grants for power and to augment infrastucture and market. The MSME sector has been the beneficiary of many Multi-lateral, Bilateral, Foundations and Donors supported programmes.

However, there is very limited documentation that examine the potential of local industry or cluster associations, leaders and local service providers to effectively catalyse the uptake of energy efficiency projects, both at the cluster level, and at the unit level. AEEE's first of its kind report on the Energy Services Performance Contracting (ESCO) market[1] had pointed out that creation of a neutral market enablement entity for awareness and facilitation, as one of the essential factors for a greater uptake of ESCO and EE projects.

According to a recent Reserve Bank of India (RBI) Expert Committee Report[2] *"MSMEs require low capital to start the business, but create huge employment opportunities"*. RBI quotes the National Sample Survey (NSS) 73rd round conducted during the period 2015-16, *"MSME sector has created 110.9 million jobs (36.04 millon in Manufacturing, 38.72 million in Trade and 36.22 million in Other Services and less than a million (0.07 lakh) in Non-captive Electricity Generation and Transmission) in the rural and the urban areas across the country"*.

The RBI Report highlights the significance of strengthening the institutional facilitation mechanism for MSMEs, and cites global best practices that can be adopted.

APPROACH

This papers reviews and compares two different MSME Clusters and the facilitation role played by the cluster associations, leaders and the local service providers for energy efficient transformation is presented in this paper.

(1) The Federation of Ceramic Industries in Thangadh, Surendranagar, Gujarat where a number of donor agencies and ministries have implemented technology up-gradation programmes[3] is a good example of active local entities.

(2) Faridabad Small Industries Association where IAMSME (Integrated Association of Micro, Small and Medium Enterprises) has facilitated access to Government of Haryana, MSME support programmes, grants, incentive and subsidies[4]. The Cluster experience illustrates how change agents can significantly alter the prospects for improved growth and competitiveness.

CATALYSING THE MSME TRANSFORMATION

The Indian and the Global economy is poised on the cusp of an impending economic downturn. Several programmes have been launched over the past decade that aims to build up the resilience of the MSME sector, bring them into the mainstream, and improve the quality of products, and diversify product range according to changes in demand and survive global competition. The experience of two MSME clusters in two different states, show an interesting contrast of cluster dynamics and resilience. The central focus is on improvement in energy efficiency and adoption of clean technologies that contribute to climate change mitigation, and job creation.

The Thangadh Ceramic Cluster:

Thangadh is located in Surendranagar District of Gujarat, is one of the 24 energy-intensive MSME clusters under the GEF-UNIDO-BEE project titled *Promoting energy efficiency and renewable energy in selected MSME clusters in India*[5]. The 225 ceramic units in the Thangadh cluster fall under three distinct types based on their primary products: pottery, insulators, and sanitary ware. The Federation of Ceramic Industries (Registered as Panchal Ceramic Association Vikas Trust - PCVAT), is an active in the cluster from pre-independence era. UNIDO project builds up on the strength and capabilities of various local entities.

The Project Management Unit housed in BEE, ensures the synchronisation of the programme with other key ministries, such as MNRE and MSME, the Office of DC-MSME, the state designated agencies and Industrial Development Corporation.

A number of MSME units have adopted the EE measures recommended under the GEF-UNIDO programme, with support from the Cluster Leader and the Energy Management Cell (EMC) set up through the cluster association[6].

At the ground level UNIDO works closely with Cluster Associations through Cluster Leaders. UNIDO in principle, does not endorse any associations, facilitators or Local Service Providers (LSPs). However, these entities do play a key role in the successful off-take and early replication of EE projects. The adoption of high-efficiency technologies and retrofit strategies is playing an essential role in reducing the energy intensity of economic activities and avoiding the need for new energy supply.

The Thangadh Ceramic Units used their collective bargaining power to purchase energy efficient technologies and reap the benefit of lower energy costs and efficient servicing. The short and medium term benefits include monetary saving and reduction in CO_2 emissions.

The case example of adoption of an energy efficient technology, brings out the partnership and collaborative approach of the project.

For instance, among sanitary ware units, a key stage in the manufacturing process is the shaping of sanitaryware by pouring the clay slurry into plaster-of-Paris moulds, which is done in casting rooms. During the shaping process, the moulds absorb water from the clay slurry and become wet. The moulds have to be completely dried in 24 hours so that the shaped ware can be cast the following day.

With humid air slowing down the natural drying of moulds, units have been using conventional ceiling fans in their casting rooms to expedite the drying process. Typically, one ceiling fan is required for every four moulds, and each unit has about 600–800 fans which run for almost 20 hours a day (depending on ambient weather conditions).

Energy audits showed that the conventional fans were low in energy efficiency, with most of them consuming 70–75 W at full speed. Also, the performance of fans was poor due to age: typically, a unit incurred monthly expenditure of INR 5,000–8,000 (about USD 70-110) on maintenance and repair of fans. Based on the project recommendations, sanitary ware units are replacing their conventional fans with energy efficient BLDC (brushless direct current) fans which consume only 28 W at full speed.

Other benefits offered by the BLDC fans are: (1) Elimination of friction and associated power loss (2) Better flexibility over controlling motor speed (3) No spark and minimal electrical noise, as no slip rings or mechanical brushes are used (4) The BLDC fans come with three years on-site replacement warranty.

With the various interventions of the GEF-UNIDO-BEE project, the MSME units in the cluster achieved an annual energy savings of about 1100 tonne of oil equivalent (toe) and annual monetary benefits of Rs. 58 million against an investment of Rs 90 million. These energy conservation initiatives helped in mitigation of 6200 tonnes of carbon emissions.

The Federation Cluster leaders, and LSP (in this case Atomberg the BLDC fan manufacturer) have played a key role in the success of the programme. Moreover, the concept of cluster leader, has also helped in scaling up and replicating the project activities in a large number of units and can be replicated in other clusters.

The industry associations have a role in promoting EE, they can play a role in monitoring the benefits of these programme, and achieve the firms and clusters greenhouse gas (GHG) emissions reduction targets, and cost-effectively support climate change mitigation. Energy efficiency is the most critical element in keeping the door open to the globally agreed 2°C target through to 2020 at no net economic cost.

IAMSME, Faridabad:

The district of Faridabad, in Haryana is a prominent business and industrial centre, second only to Gurugram, covering an area of 2,151 sq. km. Adjacent to the southern part of Delhi, it is well connected to the National capital and Gurugram through a road and rail network.

The main industries in Faridabad are light engineering goods, metal goods and automotive components. It complements the automobile industries located in Gurgaon. The 500 small and medium enterprises in Faridabad, mainly auto component manufacturers, are finalising plans to invest over US$ 30 million (approx. INR 2130 million) for technology improvement and capacity expansion.

MSME sector in general has been facing the challenges of poor access to markets, credit, technology and infrastructure, low level of awareness of policies and programmes. The MSMEs industrially backward districts need additional support. State Government have provided subsidised power to MSME, the Association has actively promoted the ongoing programmes and schemes of the government. However, in an environment where economic growth is slowing down the MSMEs would need broad-based intervention.

IAMSME, works in partnership with Faridabad Small Industries Association and plays a pro-active role adoption of new technology and business models. It plays the role of a one-stop solution centre for the MSMEs and provides tried and tested, affordable, customised and guaranteed solutions that save time, energy and costs. This industry association facilitates the growth and development of small businesses across India through its network of chapters. The Association's promotional programmes for energy efficiency have benefited several of the SME units.

Going beyond what typical industry associations do, the IAMSME provides a wide range of technical, financial, legal and business advisory services to its Members. Significant among them are credit facilitation, technology transfer, risk management, skills upgrading, energy efficiency services, solar power integration, lean manufacturing, IT services and solutions and sharing of best-practices.

IAMSME’s strength has been to channel the state government’s subsidies and incentives to its Members. Haryana Government has announced a slew of incentives and grants to MSMEs, especially in targeted clusters with high potential. These include: Government direction to Banks to finance SMEs for acquisition of equipment, enhancing of energy efficiency in plan and processes.

Through the Association, the SME units can avail bank financed up to 75% of the total project cost, subject to maximum of INR 10 million, and minimum amount of loan INR 0.5 million (USD 7,000).

Two of the programmes relevant to the adoption of energy efficiency are: (1) Fifty per cent subsidy given for purchase of energy efficiency equipment, (2) Non-collateral financing of energy efficiency projects. The objective is to draw out replicable best practices and lessons learned.

The Fifty per cent subsidy on energy efficient machinery up to Rs 20 lakh (USD 27,000), as a part of technology upgradation and modernisation. Around 4 to 5 units have availed of this scheme launched in February 2019. However, the scope is much larger and the association is aggressively promoting the adoption of efficient technologies based on the success achieved by the early starters.

IAMSME also facilitates the access to finance from SIDBI, other Banks and NBFIs. However, in comparison to the number of potential units who can benefit from these schemes, the number of units who have availed of them is presently low. A key factor is the low appetite for risk and the need to create better awareness of financial management practices among the MSME units.

The Association efficiently leverages the Schemes and programmes of the State and central government and development of new business models. By adopting the latest communications and IT practices, IAMSME share the success stories and experience among its various Chapters and Members in different states. This in turn helps regional chapters to leverage State-level schemes of different State governments.

IAMSME's intervention has enabled a few individual success stories. Significantly these have been in the Auto component segments. There are good examples of units which have successfully gained an entry into the global supply chain for auto components and ancillaries. However, replication is a challenge to the late entrants who are caught in the downward spiral of the market slow-down in the Automobile sector. This can dampen the interest of the cluster in adopting global best practices.

ANALYSIS OF THE EXPERIENCES

Gujarat MSME Cluster: The UNIDO program through the successful involvement of cluster association and leaders have motivated the MSME units to actively participate and benefit from the Cluster Development programs.

(i) MSMEs are willing to implement EE/RE measures and make EE/RE investments to reduce overall carbon emissions and improve local environment. The pre-conditions are:

- There should be sufficient support to the Units by the local suppliers of EE and RE products and services and the cluster-based Energy Management Cells;
- It is important to showcase successful EE and RE technologies adopted to local needs and the relevant best practices
- Information and Access to financial support
- Highlight the Return of Investment (ROI) for investments and specific measures which are proven and within acceptable timeframe

(ii) By successfully showcasing the experience above in 12 selected clusters, other clusters are willing to follow this EE/RE approach for early adoption

(iii) This approach can be mainstreamed into national policies and programmes for MSME development.

Haryana MSME Cluster: The leadership and initiative of the IAMSME, to build up on the State and Central Schemes has been significant. This is also a factor that has helped IAMSME to launch chapters in other states, as well as in Bangladesh. However, in comparison to the number of potential units who can benefit from these schemes, and those who have availed of the benefits is low. A key factor is the low appetite for risk in the current uncertain market scenario. The firms are of the view that the impact of Demonetisation in 2017, and the introduction of GST and its compliance requirements, have significantly impacted their growth.

IAMSME has enabled the adoption of energy efficient technology in around 40 SME units, and disbursed around INR 2.5 crore (USD 0.35 million) in subsidies and grants over the past 2 years. It aims to develop new business models and collaborative development strategies in the cluster. The association is in a position to share this experience among its Chapters in different states. This would also spur the adoption of proactive schemes by different State governments.

IAMSME's intervention has enabled a few individual success stories. Significantly these have been in the Auto component segments. Some of the units have successfully gained an entry into the global supply chain for auto components and ancillaries. However, those units which would like to adopt energy efficient technologies and processes, find themselves caught in the downward spiral of the present market situation in the Automobile sector.

This can endanger the viability of the cluster and its associations to adopt global best practices.

However, MSME sector is facing challenges in access to markets, credit, technology and infrastructure, deficient in policy outreach and awareness. The MSMEs also need extra support especially in industrially backward districts. State Government provides subsidised power to MSME. Cluster Associations have actively promoted the EE programmes of the government. The overall economic conditions of the clusters would need broad-based intervention.

CONCLUSIONS & RECOMMENDATIONS

1. The industry associations can play a key role in providing services to identify energy efficiency opportunities through service providers.
2. Such services can be paid for on a case-to-case basis, or through a general subscription service which the associations charge to their members.
3. Associations can bundle package of services to their members and their access to finance, and in turn create an ecosystem where the benefits and knowledge of energy efficiency and clean technologies are shared.
4. The industry associations can also be a demand aggregator and engage with large OEMs, system integrators and local service providers to bring down prices and get better terms and conditions.
5. Beyond lobbying for incentives, subsidies and grants from the government, the associations should work to build up a sound platform where the members can discuss issues with government entities, engage with equipment vendors as well as and initiate B2B (business-to-business) forums.
6. In conclusion, economic recovery can also be characterised as coming together of factors that create a *multiplier effect*, by stimulating local demand and creating the market that can sustain itself. If there are any lessons for the MSMEs from the Indian and global *Start-up* revolution, this could be one of them[7].

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ENERGY EFFICIENCY IN POST-HARVEST MANAGEMENT IN INDIA

Tarun Garg[1], Sandeep Kachhawa[2], Gerry George[3]

[1]*Buildings and Appliances*
Alliance for an Energy Efficient Economy
Delhi, India
tarun@aeee.in

[2]*Buildings and Appliances*
Alliance for an Energy Efficient Economy
Delhi, India
sandeep@aeee.in

[3]*Buildings and Appliances*
Alliance for an Energy Efficient Economy
Delhi, India
gerry@aeee.in

ABSTRACT

An integrated and efficient cold-chain is necessary to combat the issue of post-harvest food loss and to maintain the quality of the horticulture produce in India. An integrated pack-house, with facilities such as sorting, grading, washing, drying, packaging, pre-cooling and staging cold-rooms, is the nerve centre of the cold-chain infrastructure. With ~97% infrastructure gap today, pack-houses are likely to experience exponential growth in the short term. The India Cooling Action Plan launched by the Government of India has given paramount importance to the cold-chain sector in terms of potential for reducing cooling demand and energy consumption. This paper put forward measures to incorporate energy efficiency in the upcoming pack-house infrastructure, as a critical component of an integrated and low-energy cold-chain. The paper will: (a) map the existing policy, regulatory and institutional framework governing the cold-chain sector that can impact the development of the pack-houses in particular; (b) conduct assessment of status of pack-houses in India; (c) collate relevant energy efficiency interventions by the private sector; (d) explore the best practices used internationally; (e) suggest energy efficiency improvement options through improved designs, better operational and maintenance practices and use of energy-efficient cooling systems; and, (f) provide recommendations on policy and regulatory options to the Government.

Keywords - cold-chain, pack-house, energy efficiency, cooling

CONTEXT

Agriculture plays a very vital role in India's economy, with more than 50% of its people depending directly or indirectly upon agriculture and associated sectors. However, this largest enterprise in India contributes only 17% to the GDP (PIB, 2018). This share has been declining over the years primarily due to the growth in the manufacturing and services sectors while the agriculture growth rates have been inconsistent. The industry is characterized by instability in incomes because of various types of uncertainties involved in the production, marketing and pricing. According to the Food and Agriculture Organization (FAO, 2011), out of the total farm produce, food lost between the farm gate and the market is around 40% in developing countries like India. This food wastage, however, isn't limited to one level alone but perforates through every stage; from harvesting, processing, packaging, and transporting under the broader cold-chain umbrella to the end stage of consumption. Limited cold-chain infrastructure is a significant shortcoming, resulting in India accessing only 60% of its produce. For a country with hunger issues, this food loss has tremendous socio-economic implications; in addition, and often overlooked, is also the environmental consideration owing to greenhouse gas emissions released from the decomposing food.

An integrated and efficient clean cold-chain can play a significant role in addressing this problem and transforming shortcomings into opportunities. In March 2019, an India Cooling Action Plan (ICAP), was developed through the inter-ministerial and multi-stakeholder process to synergise actions for addressing the cooling requirements. ICAP overlaps across sectors, including building space cooling, cold-chain and refrigeration, transport air conditioning, servicing, indigenous production of refrigerants, and R&D in the cooling domain. Development of an integrated cold-chain infrastructure has been proposed with appropriate market linkages, supported by adequate training and up-skilling of farmers and professionals engages in allied activities. The co-benefits include economic well-being of farmers and reduced food losses thus strengthening food security and alleviating hunger-related issues.

The inter-ministerial committee on Doubling Farmers' Income (DFI) under the Department of Agriculture Cooperation & Farmers Welfare is also an important and ambitious vision of the Government of India to revolutionise the agricultural sector in India. DFI has prepared 14 different volumes deliberating upon the issues to bring about an income revolution for the farmers of India and highlighting the critical role of efficient cold-chain infrastructure in India.

An efficient cold-chain is the means of addressing the critical issues of the agricultural sector, such as marketability and handling of agricultural produce, diversification and modernization, enhancing farmers' earning through value addition, enabling a farm to fork value chain, strengthening its inter-linkages with food processing industry, and push to exports of horticulture and processed food items.

The 2018-19 budget announced the government's agenda to develop 22,000 Gramin Agricultural Markets (GrAMs) by 2022 to organise effective market linkages, starting at first mile. These GrAMs will serve two roles: (1) a platform that facilitates direct local retail, for farmers to transact sales with the near-farm consumers; (2) primary aggregation/pooling/dispatch centres of farm produce, to facilitate the onwards post-harvest movement to market destinations that are farther afield. The GrAMs will primarily be designed with pack-houses to stage and dispatch produce. The modern pack-house with the pre-cooling system is the vital first link in the integrated cold-chain for fruits and vegetables.

With the accelerated plans for development of several thousand pack-houses across the country, right now is the critical window of opportunity to build in energy efficiency in the upcoming pack-house infrastructure, as a critical component to an integrated and low-energy cold-chain that is central to advancing farmers' economic well-being, and carries other vital co-benefits such as mitigating food losses and the resulting emissions, and alleviating hunger.

INTRODUCTION

Overview of Pack-houses in India

About pack-house:
According to the National Centre for Cold-chain Development (NCCD, 2015), pack-house is a modern infrastructure with facilities for conveyer belt system for sorting, grading, washing, drying, weighing, packaging, pre-cooling and staging. Modern pack-houses are the first step in organized post-harvest management for horticulture and are in effect the first-mile sourcing points for this sector. A modern integrated pack-house unit enables small lot sourcing of horticulture produce, and should be built close to farm-gate.

Typical pack-house process (NCCD, 2015)**:**

The flow of produce in an integrated pack-house unit includes handling on receiving the harvested goods, preliminary pruning/trimming/de- handing, sorting as per market channel and quality assessment, grading as per size and colour, packaging and labelling as first-level pre-conditioning, unitising the load to precool the packaged load, transient storage in cold room in preparation for onward transport.

Receiving area: It is covered shaded area for arriving produce to be off-loaded and undergo pre-selection and weighing

Enclosed covered sorting and grading area: It is a food handling hall with mechanised handling and cleaning equipment. Sorting is the activity at source when produce is assorted into target lots basis qualitative criteria viz. as non-edible, as to reject or dump, by quality, by shelf-life, by market value, etc. Grading is the activity at source for physical segregation of goods into optimal packing lots, after undergoing initial sorting.

Sorting and grading conveyors: Mechanised roller or belt-based system to pick and choose to produce for the next activity and capable of handling the output per day

Washing/Drying equipment: These are mechanised washing and drying lines

Packaging area: a designated area where produce is manually packaged into market lots

Pre-cooling and Storage: Pre-Cooling unit is a specialised cooling system designed to rapidly remove the field heat from freshly harvested produce and thereby prepare the cargo for subsequent travel in the cold-chain. Cold room (Staging) is an insulated and refrigerated chamber which serves as a transient storage space and is a necessary attachment to a pre-cooling unit.

Most of the Pack-houses are designed to maximize the utilization of the infrastructure based on the location and harvesting season of the crops, but the layout of a pack-house facility may differ depending upon the produce to be handled. For example, in the case of mangoes and litchis, the conveyer belt system is used, but in the case of bananas, water troughs are used in place of the conveyer belt system. In a litchi pack-house, a fumigation room is needed to have sulphur extraction, ventilation and scrubbing system, while in a mango pack-house facility, the de-sapping rack is added as a part of pre-conditioning.

POLICIES AND INSTITUTIONAL FRAMEWORK GOVERNING COLD-CHAIN IN INDIA

Various ministries and bodies govern Cold-chain in India for establishing and implementing the regulatory framework. Several assistance and subsidy schemes have been made available by these ministries for the development of cold-chain in the country. The role of key government bodies at the central level, state level and other bodies through their missions, schemes and initiatives for a holistic farm to fork cold-chain are -

1. Role of Central Government

Ministry of Agriculture and Farmers' Welfare (MoA&FW):
Mission for Integrated Development of Horticulture (MIDH) (MoA&FW, 2014)
MIDH is a centrally sponsored scheme for the holistic growth of the horticulture sector covering fruits and vegetables. While the government of India (GoI) contributes 85% of the total fund for developmental programmes in all the states except the states in North East and the Himalayas, 15% share is provided by State Governments. In the case of the North-Eastern States and the Himalayan States, GoI contribution is 100%.

Integrated Scheme for Agricultural Marketing (ISAM) (MoA&FW, 2014)
The Ministry of Agriculture launched this scheme intending to promote agri-marketing through the creation of marketing and agribusiness infrastructure including storage, incentivize agri-market reforms, provide market linkages to farmers, provide access to agri-market information and to support quality certification of agriculture commodities.

Rashtriya Krishi Vikas Yojana (RKVY) (MoA&FW, 2014)

RKVY scheme was initiated in 2007 for ensuring holistic development of agriculture and allied sectors by allowing states to choose their own agriculture and allied sector development activities as per the district/state agriculture plan. The funding pattern of the scheme has been altered in the ratio of 60:40 between Centre and States (90:10 for the North Eastern States and the Himalayan States). For Union Territories the funding pattern is 100 % central grant. Under RKVY infrastructure & assets stream, projects can be funded for functional infrastructure for collection, sorting, grading, cold storage, precooling, refrigerated vans, ripening chambers and primary processing units.

Ministry of Food Processing Industries (MoFPI):
Pradhan Mantri Kisan SAMPADA Yojana (PMKSY) (MoFPI, 2017)
PMSKY is a central scheme with an allocation of INR 6,000 crore for the period 2016-20 which will be implemented by MoFPI.

The various sub-schemes that will be implemented under PMSKY include mega food parks, integrated cold-chain and value addition infrastructure, creation/ expansion of food processing/ preservation, infrastructure for agro-processing clusters, creation of backward and forward linkages, food safety and quality assurance infrastructure, human resources and institutions

Ministry of Commerce and Industry (MoCI):
Agricultural & Processed Food Products Export Development Authority (APEDA)
For the development of export infrastructure, APEDA assistance is available for the establishment of post-harvest infrastructure for fresh horticulture produce. The financial aid (APEDA, 2014) is provided to the exporters for setting up of pack-house facilities with packing and grading lines, pre-cooling units with cold storages and refrigerated transportation, cable system for handling of crops like banana, pre-shipment treatment facilities such as irradiation, etc.

2. Role of Other Departments/ Bodies

National Centre for Cold-chain Development (NCCD):
NCCD is established to promote and develop an integrated cold-chain in India for perishable agriculture and horticulture produce including perishable from allied sectors. The main objectives of the centre are to recommend standards and protocols for cold-chain infrastructure, suggest guidelines for human resource development and to recommend an appropriate policy framework for the development of cold-chain.
Small Farmers Agribusiness Consortium (SFAC):
SFAC has pioneered the formation and growth of Farmer Producer Organizations/Farmer Producer Companies. SFAC is also implementing the National Agriculture Market Electronic Trading (e-Nam) platform.
National Cooperative Development Corporation (NCDC):
NCDC supports fruit and vegetable marketing and processing cooperatives; it not only plays a developmental role but also provides financial assistance for creating infrastructure for marketing,

processing and storage of agricultural produce in the cooperative sector.

3. Role of State Government

State Horticulture Division:
The State Horticulture Mission is a registered society in various states in India to implement the National Horticulture Mission, which is one of the sub-schemes of MIDH.

Agricultural Produce Market Committee (APMC):
APMC is a marketing board established by a state government in India. It ensures that farmers are not exploited by intermediaries who compel farmers to sell their produce at the farm gate for a meagre price and all food produce should first be brought to a market yard and then sold through auction.

State Agriculture Marketing Board:
The agriculture marketing boards are the statutory body within the state, which plays the primary role in developing and coordinating agricultural marketing system in the State.

Farmers Producers Organizations (FPOs):
FPO is a producer organization where the members are farmers. A producer organization can be a producer company, a cooperative society or any other legal form which provides for sharing of profits/benefits among the members.

Energy Efficiency Programs Relevant to Cold-Chain

Energy Conservation Building Code (ECBC):
ECBC was launched as a first step towards promoting energy efficiency in the building sector in India. It is applicable for large commercial buildings with a connected load of 100 kW and above or 120 kVA and above. ECBC focuses on building envelope, mechanical systems and equipment including heating, ventilating, and air conditioning (HVAC) system, interior and exterior lighting systems, electrical system and renewable energy, and also considers the climates zones in the country.

Although ECBC is applicable for buildings, certain aspects of the code like structure design, materials used for wall, roof and window and efficiency of motors, pumps and chillers could be referred for a pack-house.

Standards & Labelling programme (S&L):
The Bureau of Energy Efficiency initiated the Standards & Labelling programme for equipment and appliances to provide the consumer with an informed choice about energy saving and thereby the cost-saving potential of the relevant marketed product. The energy efficiency labelling programs under BEE are intended to reduce the energy consumption of appliance without diminishing the services it provides to consumers. Currently, the S&L programme is available for 23 appliances out of which equipment like room air conditioners, tubular fluorescent lamps, LED lamps, induction motors, pump sets, ceiling fans, DG sets and chillers can be applicable for a pack-house as well.

India Cooling Action Plan (ICAP):
The India Cooling Action Plan (ICAP) released on 8 March 2019 is a turning point in the advancement of the future of cooling in India. Some of the key recommendations made in ICAP for the development of the cold-chain include encouraging the development of cold-chain infrastructure with the use of low-GWP refrigerant-based energy-efficient cooling systems, standardising all design, construction and associated specifications for small, medium and large cold-chain infrastructure components, linking the incentives being provided for the development of cold-chain infrastructure with the adoption of energy-efficient design, improving construction and maintenance practices, providing specialized training facilities for cold-chain professionals and technicians to promote proper utilization and operation of technology, as well as energy efficiency and providing training to farmers so that they can better manage their produce both pre-harvest and post-harvest

Gaps in Policy, Institutional and Regulatory Framework in the Context of Energy Efficiency

Institutional gap:
The Bureau of Energy Efficiency (BEE) has a key role to frame guidelines on energy-efficient design and operation of pack-houses in India, which is yet to be defined. Enhanced inter-ministerial coordination between the Ministry of Agriculture and the Ministry of Power would be required to integrate energy efficiency in the cold-chain infrastructure design and operation.

Policies and regulations:
BEE has defined policies and regulations related to energy efficiency for industries, buildings and appliances. These policies and regulations could apply to some of the equipment and structural components in the cold-chain sector.

The financial assistance under MIDH has been linked with energy-efficient equipment, but the efficiency of equipment is not defined. NCCD system design guidelines explain the possible options to achieve energy efficiency in a pack-house, but equipment-wise energy performance specifications need further development.

Data reporting:
Data reporting guidelines to track and monitor the energy consumption at the facility and equipment level and the throughput capacity of the pack-house need to be formulated.

STATUS OF COLD-CHAIN INFRASTRUCTURE IN INDIA

The cold-chain infrastructure in India consists predominantly of a large footprint in refrigerated warehousing space – reported to be the world's largest, at about 134 million cubic metres in volume. Per NCCD, this capacity is primarily designed for bulk, long-term warehousing of certain crops - mainly potatoes and red chillies. Comparatively, exceptionally few cold stores are designed as distribution hubs, at the front end of the supply chain. Since the majority of cold stores in India are single-purpose warehouses, due to the seasonality of produce, some of their capacity can remain idle for 2-3 months in a year. Also, such cold stores are not linked with other cold-chain components to create the uninterrupted supply chain.

The other requirements ranging from source to market include modern pack-houses, refrigerated transport, ripening chambers and last-mile connectivity to retail outlets. India has done reasonably well in terms of creating capacity for cold stores, but it significantly lags in terms of creation of pack houses, reefer vehicles, and ripening chambers.

Table 1: Cold-chain Infrastructure gap in India (NCCD, 2015)

Type of Infrastructure	Infrastructure Requirement	Infrastructure Created	Infrastructure Gap
Pack-house	70,080 Nos.	249 Nos.	69,831 Nos.
Cold Storage (Bulk)	341,64,411 Metric Ton	318,23,700 Metric Ton	32,76,962 Metric Ton
Cold Storage (Hub)	9,36,251 Metric Ton		
Reefer Vehicles	61,826 Nos.	9,000 Nos.	52,826 Nos.
Ripening Chamber	9,131 Nos.	812 Nos.	8,319 Nos.

APEDA Recognized Pack-Houses

Around 200+ pack-houses are registered under APEDA at present. These pack-houses are utilized for handling and processing of all horticulture produce including fresh fruits and vegetables for export. The APEDA recognition for pack-house is granted for multiple produce for which appropriate facilities and procedural compliances commensurate with matching infrastructure facilities based on an inspection done by the inspection committee. Various stakeholders are involved in getting the responsibilities for compliance of procedural formalities for quality export as per the importing countries. The fruits and vegetables from India can be exported to the European Union countries based on the phytosanitary inspection at the pack-houses approved jointly by National Plant Protection Organization and APEDA where adequate facilities for inspection, examination are available, and the produce is packed under the supervision of plant quarantine official. Phytosanitary status of the inspected consignments is secured by proper storage in demarcated quarantine area at the pack-house, transported by clean and disinfected vehicles. Also, loading of the shipment at the exit point is ensured in clean and disinfested cargo containers preventing cross-contamination. The approved pack-houses are responsible for maintaining the backward traceability information for the consignment.

Pack-House Infrastructure Addition

As per the India Cooling Action Plan (MOEF&CC, 2019), while the cold-chain sector represents a small portion of the aggregated cooling demand from all sectors, it is poised for significant growth shortly. India has a large inventory of cold storages, but the other elements that make up an uninterrupted cold-chain including pack-houses, reefer vehicles and ripening chambers are mostly missing. With around 500 pack-houses in India at present, the number is likely to grow to 55,000 by 2027 and 1,25,000 by 2037.

Energy Consumption in A Pack-house

Pack-houses use electricity to power a wide variety of machines required to transform the harvested product into attractive, pre-cooled, palletized ready for transport to port terminals. Having a measure of the amount of energy used in these various operations is the first step in bringing about an awareness of the areas that should be targeted to conserve electricity and fuel usage. In isolation, however, such information is of limited value. More importantly, pack-house managers need to know how the energy usage and costs of their units compare with that of other similar farming and processing operations.
As per the India Cooling Action Plan, at present, the energy consumption in pack-houses in India is estimated to be 21 GWh. Projections show that this

will grow ~100X to 2.4 TWh by 2027 and further double to 5.2 TWh by 2037. The refrigeration system installed for pre-cooling and staging cold room is the most energy-intensive process in a pack-house. The overall power consumption can be reduced by employing energy-efficiency measures such as pressure regulation valves for evaporator and condenser, electronic expansion valve, thick PUF wall insulation, high-speed roll-up doors, air-curtains, and variable-frequency drive (VFD) for compressor & fan control. As per ICAP, the overall energy saving potential in cold-chain sector is around 8-12% by employing efficient compressors, improved insulation and optimized operations. The potential improvements mainly consider energy-efficiency of the infrastructure and cooling equipment, choice of low GWP refrigerants and refrigerant-related servicing practices.

Private Sector Initiatives in Reducing Energy Consumption in Pack-houses

Plug and Chill technology:
PLUGnCHILLTM Mobile is a 3 in 1 solution for the field as produce at the farm level can be directly stored and cooled in the container. The cooled produce can then be sold to market through distributors or directly to the end consumers.
The key features of the technology include – (a) manufactured in India with global application (b) Uses Thermal Energy Storage technology using Phase Change Materials (c) Maintains temperatures for 12-24 hours without additional energy (d) Green technology that reduces dependence on fossil fuel – reduction of 1000 litres/annum per small commercial vehicle e) Enables creation of a cost-effective Cold chain to reduce annual food loss in India

Eco-Frost technology:
In most cases, farmers are generally forced to sell their produce in the close vicinity. When Ecofrost system is installed, farmers could pre-cool the produce which helps in enhanced shelf life and makes it better suited for long-distance transportation. This enables the farmer to maximize his returns by taking produce to the farmer market than selling in the local market.
Key features of the technology include (a) 30 hrs battery-less backup, (b) Pre-cooling up to 4 deg C, (c) remote sensing & predictive analysis, (d) Size of the unit is 20x8x8 ft with storage capacity up to 5 Metric Ton, (e) All Ecofrost units come integrated with IOT module and a mobile app to monitor, control & service the unit, and also inform about cold room utilisation.

INTERNATIONAL BEST PRACTICES

As per FAO (FAO, 2012), the basic requirements of a pack-house facility is to ensure adequate protection from sun and rain, proper flooring, good ventilation and lighting. The success of a pack-house facility depends on the volume of produce to be handled. The larger the amount, the higher the utilization of the facility and its equipment and personnel; this translates into reduced costs for the facility. As the growing season of many crops is limited to certain months of the year, efforts should be made to identify off-season suppliers or alternative commodities to extend operations. The factors to be considered in the pack-house design include:

Functionality

For example, receiving areas for freshly harvested commodities may be left open to allow air circulation and facilitate unloading, although they should be shaded to avoid direct exposure to the sun.

Quality and Volume of Produce

Walls allow heat and ethylene to accumulate within the facility, thereby increasing the rate of ripening and deterioration of produce. The facility must be large enough to accommodate the volume of produce to be handled.

Worker Safety and Comfort

Working conditions inside the facility should minimise fatigue and physical stress. It is important to monitor temperature and relative humidity, light levels, equipment ergonomics and the location of needed materials, tools, and equipment (easy to find, and easily accessible).

Level and Scale of Operations

In cases where cold storage facilities are limited, compatibility issues may need to be considered such as storage temperature, relative humidity, ethylene sensitivity and odour absorption.

APPROACH FOR EE IMPROVEMENT IN PACK-HOUSES

Taking forward the recommendations of the India Cooling Action Plan, the authors suggest the following approach to ensure that the upcoming pack-house infrastructure is built and operated in an energy-efficient manner.

Policy and Regulatory Measures

Owing to huge investment requirements, government subsidies and incentives play an important role in pack-house infrastructure development in India. Linking energy efficiency with these various government subsidy and incentive schemes will ensure that only energy efficient pack-houses receive financial assistance.

Awareness Building Among Private Investors

Infrastructure developers and investors are generally not aware of energy efficiency; hence, their design consultants and turn-key contractors make key decisions about the design, equipment and technology selection. The developers and investors once convinced about the long-term benefits of creating an energy-efficient infrastructure will lead to the essential market pull for energy-efficient solutions. The designers along with the technology providers, assured by the investors shall be encouraged to design and propose innovative low energy cost-effective solutions as per the developer requirements.

Crop Care Guidelines

The first step in designing a pack-house is a scientific understanding of the crop care requirements for the produce being handled. Drawing from the research of various post-harvest institutes in India (Punjab Horticultural Postharvest Technology Centre, Central Institute of Post-Harvest Engineering & Technology, etc.), international institutes (University of California, Davis) and other good practices (FAO), customised guidelines for Indian conditions to ensure optimal crop (fruit/vegetable) care needs to be developed and made available in the public domain.

Pack-House Design Guidelines

Post the development of crop care guidelines, the next step is the corresponding design and development of various post-harvest treatment facilities for enhancing the produce's shelf life and preparing it for the onward journey to distant markets. Pack-house development still being a small niche, the expertise required is far and few. There are no standardised guidelines for pack-house component selection, process flow, material flow for typical pack-houses. The functional requirements of a pack-house such as sorting, grading, packaging, etc. vary from produce to produce and are carried out in a combination of manual and automated processes. The most energy-intensive operation of a pack-house involves rapid cooling to remove the field heat of the produce. Guidelines should be developed for the selection of pack-house components, design of process and material flow, design of precooling and cold rooms to ensure the best possible crop care with optimal energy use.

Operation and maintenance (O&M) and energy performance reporting

Guidelines for periodic O&M and energy performance reporting are vital towards ensuring the energy-efficient operation of pack-houses. Energy performance reporting shall create a feedback loop for O&M and also gradually help create energy performance benchmarks for various pack-houses across India.

CONCLUSION

The Government's accelerated plan to build new pack-houses in the near term is vital for addressing a critical gap in the cold-chain infrastructure, but it also carries essential socio-economic ramifications: the economic well-being of farmers, hunger alleviation and a more balanced and nutritious diet for the masses in the country. Safety, global standards of quality, enhanced efficiency and investments need to be the foundations on which the pack-houses are to be built. Thus, while it is decidedly important to minimize the energy consumption footprint of pack houses, it is also very important to do this quickly, and in a standardised manner that is easy, feasible, affordable and replicable.

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PCM BASED HYBRID DEVICES FOR REFRIGERATION

Shreyas Srivastava[1], Bhuvnesh Kumar[1], Bhanu Verma[1], Nidhi Agarwal[2], Vishnu Sasidharan[3]

[1]*Application development*
Pluss Advanced Technologies Pvt. Ltd.
Gurgaon, India
shreyas.srivastava@pluss.co.in

[2]*Research and Development*
Pluss Advanced Technologies Pvt. Ltd.
Gurgaon, India
nidhi.agrawal@pluss.co.in

[3]*Business Development*
Pluss Advanced Technologies Pvt. Ltd.
Gurgaon, India
vishnu@pluss.co.in

ABSTRACT

Poor cold chain infrastructure is responsible for 40-50% of total losses of food produce. Commercial freezers and coolers, meant for food and beverages, rely on continuous power supply to operate. This incurs high running cost due to electricity consumption in an uninterrupted manner. Incorporating phase change materials (PCMs) for thermal energy storage (TES) make these devices energy efficient by 15-20%. PCM provides temperature backup of upto 16 hours during power outages. PCMs have the ability to store and release a large amount of thermal energy under appropriate temperature conditions. Two PCMs: sav*E*® HS 23N (stores energy at -23ºC) and sav*E*® HS 01 (stores energy at +1ºC) are the appropriate temperatures for cold storage applications. PCM based systems, once charged, reduce the frequency of compressor at which it cuts-in, thereby saving on starting current. The concept has also been utilized in refrigerated trucks, where the PCM is allowed to charge with an outdoor unit during non-functional hours. This reduces the diesel consumption by 30-50%. Over **50,000** freezers and coolers have already been integrated and deployed with PCM technology in India with several large/small scale manufacturers and a major OEM commercially adopting it on large scale. The freezer market in India is expected to attain a value of USD 197.8 million by 2025 from USD 127.5 million in 2017. The current market penetration for PCM based freezers is 2%. In this paper, detailed investigation and installations results have been presented. The scope of the work is focused on aspects like phase change materials (PCMs), their use for energy storage, practicality and advantages of using such systems, and their effect on food quality.

Keywords—*phase change material (PCM), thermal energy storage (TES), energy efficiency, referigerated trucks, greenhouse gas emission, chest freezers, coolers, micro cold rooms, renewable energy, solar energy.*

INTRODUCTION

Commercial refrigeration units are among the most energy demanding systems in the cold chain industry due to their continuous operation [1]. Similar is the situation with refrigeration units installed in reefer trucks, which continuously draw power through petrol or diesel. Burning fuel account for approximately 17% of greenhouse gas emission (GHG). Although, recent developments in technology have introduced multiple alternatives to reduce the GHG [2], an overall performance improvement is mandatory to reduce indirect emissions and energy consumption.

There are always temperature fluctutations in industrial freezers/coolers mainly due to door openings and power outages. Many techniques have been tried and tested to reduce energy consumption using high efficiency compressors, evaporators and condensing units, good quality insulation material or integrating thermal energy storage systems (TES) [3]. Research work have been carried out to prove that PCMs provide high heat storage capacity and isothermal behavior during charging and discharging compared to the system with sensible heat storage [4]. PCMs when integrated with conventional freezers and coolers, it enables the system to store energy. During power outages or while the truck is on the go, stored energy in the PCM maintains the temperature of the room/container. Every product has different storage conditions to maintain qaulity and texture. For example, chocolates should be preserved in the temperature range of 15-25ºC, fresh fruits and vegetables should be stored in an ambient of 2-8ºC, meat should be preserved in the temperature range of -15 to -20ºC, while ice-creams should be kept in the temperature range of -18 to -24ºC. Therefore, choice of appropriate PCM is crucial. In general, PCMs available with Pluss Advanced Technologies for different applications is shown in Figure 1. PCMs can store energy at constant temperature corresponding to its phase-transition temperature. PCMs formulated for such applications should have latent heat higher than 200 kJ/kg and thermal conductivity atleast 0.5 W/mK. They melt/freeze congruently with almost no subcooling and should be chemically stable, low in cost, non-toxic and non-corrosive.

The global market of refrigerated food was expected to reach almost $200 billion in the year 2014 [5]. As we are stepping into the tech savy world, consumers demand high quality products. There is no space for rotten and spoiled eatables. To match this pace, manufacturers are paying more attention to fresh and frozen food products. As a result, significant developments in the cold chain logistics is in high demand. Controlled temperature storage devices and sustainable cold supply chain is the need of the hour.

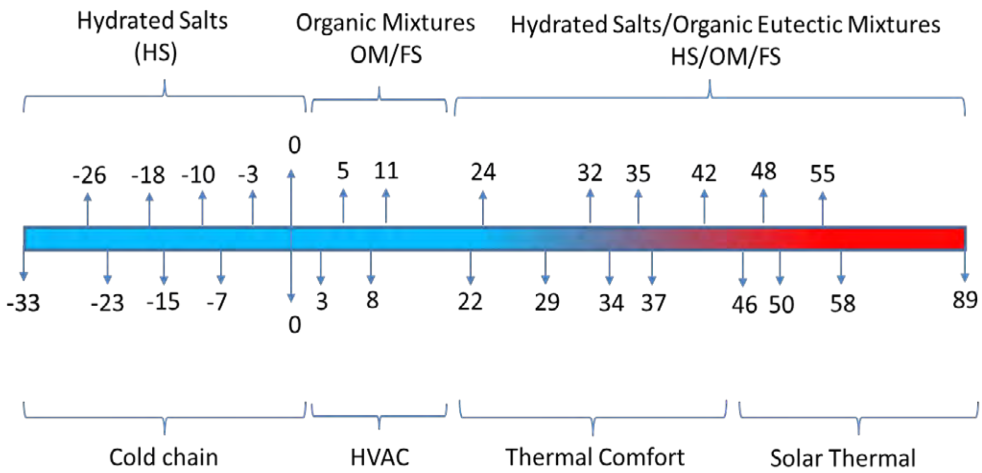

***Figure 2*: PCM categories along with application range**

Transport logistic solutions at present are based on refrigerated vehicles which use fossil fuels to operate. Due to this reason, the temperature controlled logistics becomes more expensive than the cost of goods. There is, consequently, an urgent need for shift of conventional cooling systems to non-fossil fuels based refrigeration systems. It has a huge potential in bringing down the operational costs and also reducing GHG.

Frozen and chilled products have only one major requirement, i.e., controlled storage conditions.

Major percentage of population in the country is dependent on agriculture for livelihood. Although it is important to increase productivity, it is also equally important to manage the products well after the harvest. The wastage is 0.5-4% in food grains and 4%-18% in different horticultural crops. It is thus necessary to take required steps in terms of post-

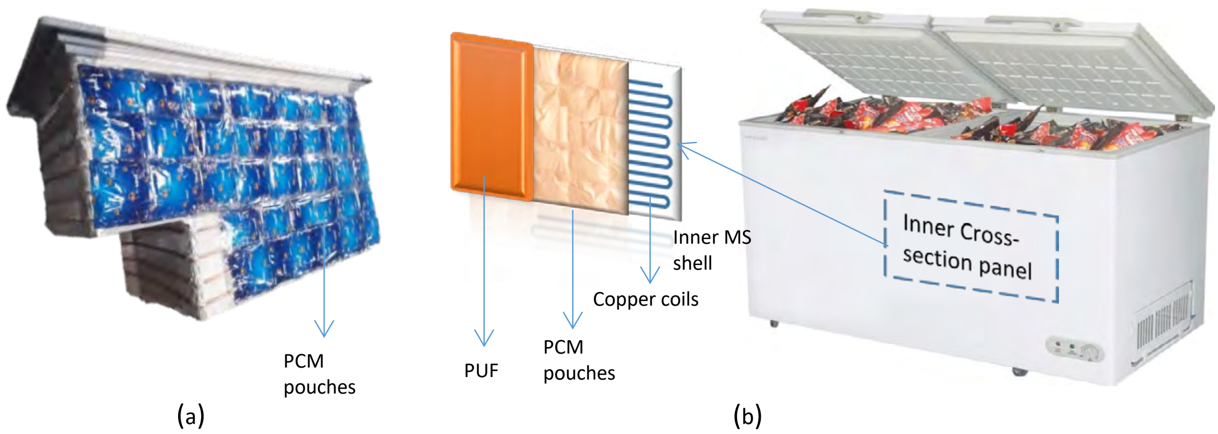

***Figure 1*: (a) PCM pouches wrapped around a chest cooler (b) Cross-section representation of PCM based freezers/coolers.**

harvest management at the first mile operations i.e. at the farm level to check and reduce the value loss of produced farm products. With respect to this, there is a direct relation between the availability of power and the dependency of the cold room facilities. It is impossible to operate working cold room for 18-20 hrs. without electricity. Alternately, diesel generators are used as a power source, which incur huge costs and are unviable as well.

A PCM based solar micro cold room, which is a small-scale PCM based solar powered cold room, can be used to store fresh fruits, vegetables, exotic and temperature sensitive flowers along with processed and perishable food commodities. This is a pioneering product in the cold chain space that bundles various innovations together.

METHODOLOGY

PCM integrated models of chest coolers, chest freezers and referigerated trucks have been studied in this paper. The PCM pouches/panels were integrated with conventional chest coolers and freezers, referigerated vehicles and cold rooms. PCMs sav*E*® HS01, sav*E*® HS23N, sav*E*® HS10N and sav*E*® HS33N were used for this study.

PCMs in chest coolers and freezers

Conventional chest coolers and freezers are available in two variations – chilled (2 to 8ºC) and frozen (-24 to -18ºC). PCMs suitable to each type of freezer was chosen - sav*E*® HS01 and sav*E*® HS23N - encapsulated in pouches. PCM pouches were placed along the inner walls. A schematic explaining the integration of these PCMs in such units is represented in Figure 2.

Working mechanism

Each freezers and coolers is integrated with 25 to 35kg of chosen PCM. The system can charge the PCM in 36-48 hours in the first run, with no payload. After one freezing cycle, freezer/cooler were be loaded as per requirement.

As shown in Figure 2, the PCMs were first encapsulated in multi-layered nylon pouches. The pouches were then placed along the copper coils circulating the refrigerant. The pouches can withstand +70ºC and an evenly distributed normal pressure of upto 2.5kg/cm^2. The choice of such an encapsulation is made while ensuring the following criteria:

- It should be strong, flexibile, corrosion resistant and thermally stable.
- Has good barrier properties against dust and moisture.
- Should be able to seal through contamination

To insulate the pouches, the insulation material, poly urethane foam (PUF) was used followed by an outer covering to protect insulation and for aesthetic looks.

In India, OEMs like Icemake Refrigeration Pvt. Ltd., Western Referigeration and Voltas are the early adopters of this technology. Rinac India Pvt. Ltd., Bangalore, are the pioneers for integrating PCMs in the reefer trucks. Today, more than 50,000 nos. of such commercial chest coolers & freezers are in use. There are more than 200 trucks running on roads using PCM technology.

***Figure 3*: Freezers and coolers with and without PCM under test at an NABL accredited lab in Gurugram.**

***Figure 4*: (a) PCM filled metallic plates mounted in insulated reefer trucks; (b) Trucks on standby mode while PCM is charging; (c) Compressor power port for charging the PCM plates.**

PCM in refrigerated trucks

Use of PCMs as a thermal energy storage (TES) enables the transportation of goods at a constant temperature while minimizing the dependency on diesel/petrol for continuous running of cooling units in the reefer trucks at the same time. The PCM filled encapsulation units, which are mounted on the insulated containers (*Figure 4*), are charged using electrically operated compressor during the non-operational hours (let's say during the night time of 8-10hrs), and then for the next 14-16 hrs it is the PCM which assures that the required temperature is maintained.

PCM in Micro-cold rooms

The solar powered cold room with thermal backup enables storage of fresh produce by constantly maintaining a temperature in the range of 2°C to 8°C or (-25)ºC to (-15)ºC throughout the day. Each such system has a dimension of 20ft x 8ft x 8ft. Solar panels are mounted on the rooftop of the structure. These panels capture solar radiation during day time. Panels run the compressor via special drive. Sizing of

(a)

(b)

***Figure 5*: (a) Farm produce kept inside the solar micro cold room; (b) Community people using the cold room for daily farm produce storage.**

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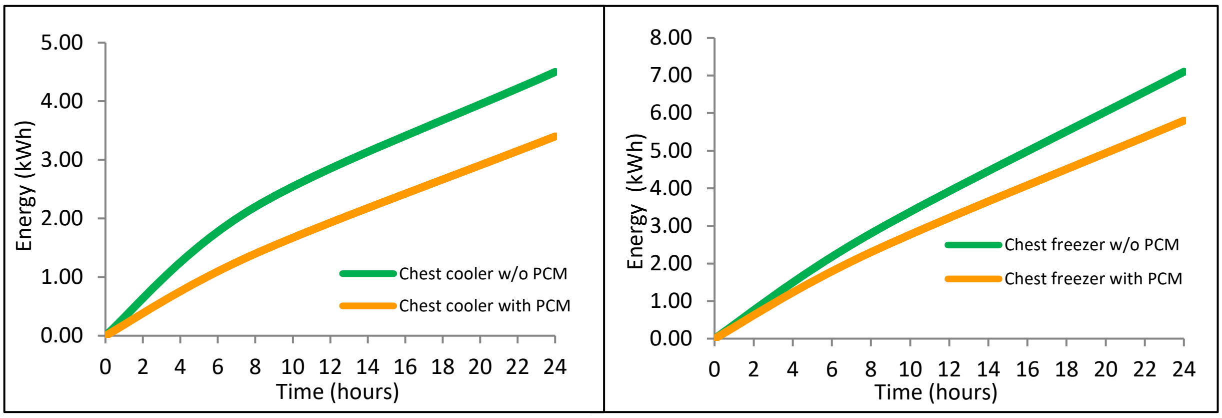

***Figure 6*: Energy Consumption Curves for 24hrs. duration.**

the compressor is done to maintain the temperature in the cold room and charge the PCM simultaneously during sunshine hours. Quantity of PCM, layout of PCM panels in the room is designed to control the temperature during off-sunshine hours. A PCM integrated solar cold room in use could be seen in the above *Figure 5*.

EXPERIMENTAL RESULTS

PCM in chest freezers and coolers

During the field trials, it was observed that the freezers and coolers integrated with PCMs provide thermal backup of 16 hours in an ambient of 35-40°C and relative humidity (upto 80-90% for extreme case testing). Moreover, thermal performnace of PCMs help in replacing 110 litre of glycol-water mixtures used in refrigeration industry with 30kg of PCM in 300 litre capacity freezers.

Apart from thermal efficiency, it was also observed that PCMs reduce electrical consumption of commercial chest freezers and coolers by 20-25% as compared to the conventional units as shown in Figure Figure 3. In an experimental study conducted under the supervision of UNIDO (United Nations Industrial Developoment Organisation), CII (Confederation of Indian Industries) and industrial partner Pluss Advanced Technologies Pvt. Ltd., Gurugram (setup as shown in *Figure 3*), it was observed that the refrigeration systems using PCM has 25-30% lower compressor cut-in/cut-off frequency per day as compared to the conventional systems. This results in low current withdrawl, which in turn saves running/operational cost. *Figure 6* depicts comparison between power consumption curves of machines with and without PCM. As a clear indicator, the user saves approximately 2-3 units of electricity per day per system. Therefore, on an annual basis, this saving is equivalent to approximately INR 8,100 per cooling unit.

The additional capital expenditure of implementing PCMs in a 400 litre capacity freezer is approximately INR 6,000. This increase in cost includes the cost of raw material, installation and other changes in the system. A conventional freezer of the same capacity costs around INR 25,000. Since, the monthly savings while using PCM based freezers is (7.5units-5units) x INR.9 x 30days = INR 675. Accordingly, the return on investment (ROI = Additional CAPEX/Montly savings) is achieved in 9 months (INR 6000/INR 675).

PCMs in referigerated trucks

The temperature backup curve under rigourous test conditions is shown in the figure 7. It shows the impact of multiple door openings on the frozen temperature being maitained inside an 8ft x 5.5ft x 5ft insulated container (80mm PUF insulation) for upto 10 hours using 120kg of HS33N (stores energy at -30°C) PCM.

One more major advantage of using such a system is that the truck can run on compressed natural gas (CNG) cylinders which add to more savings. PCMs ranging from -33°C to 0°C are suitable to meet the cooling requirements of product like meat, frozen food, fresh vegetables, ice creams and similar perishable products. Integrating suitable PCM to meet transportation requirements of sensitive goods has a significant impact on diesel consumption. It cuts down the diesel consumption upto 50-60% directly, along with precise temperature control by implementing TES system.

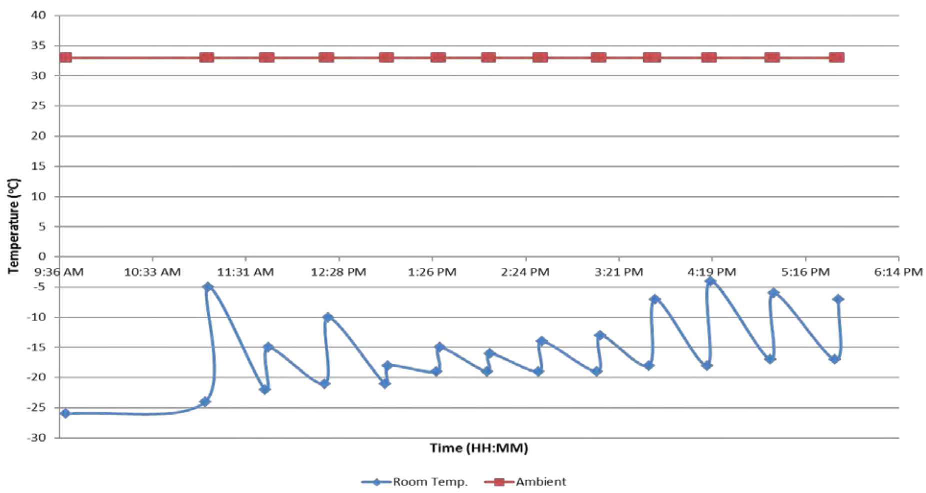

***Figure 7*: Backup performance curve of PCM integrated 8ft. reefer container maintaining -24 to -18ºC and with hourly door openings**

In one such refrigerated truck of dimensions 8ft x 6ft x 6ft, if we compare the PCM plates integrated cooling system with a conventional diesel operated compressor unit, the savings on its running cost are exceptionally high. The system is charged (or cooling is stored in PCM) during the non-operational hours using grid-power supply. As a result, there is almost 50% cost saving. Running cost of conventional reefer trucks is INR 6-7 lakhs per annum. However, running cost of PCM based trucks is INR 2.5-3 lakhs. Payback period of PCM based systems is estimated to about 4-6 months.

PCM in solar based micro cold room

Data collected from a solar based micro cold room in Nepal is shown in *Figure 8*. The system has been sold to the farming community to store the fresh produce. The stored fruits and vegetables help to restore the produce for over a month. The installation site is deprived of electricity. Hence the system runs on solar power alone.

System can also be designed in combination (or hybridized) with any other source of power as and when needed. Owing to the endless opportunities one can have using such innovative system high initial investment in this technology, as compared to conventional cold room systems, should never be the prime concern.

Due to the unavailability of the good transport network and lack of electricity in remote locations across different villages in country, the wastage of perishables is more and subsequently the loss of income to the farmer. PCM based solar micro cold room is enabling farmers to store tomato, peas, potatoes, cauliflower, amongst other produce. The benefits include:

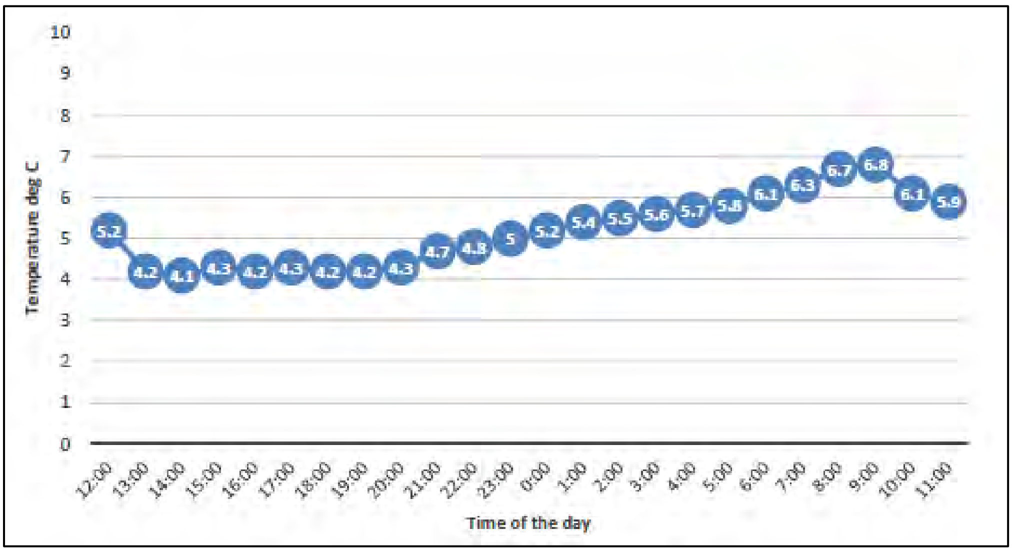

***Figure 8*: Monitored temperature inside PCM based solar micro cold room.**

- Improved quality of perishables produce due to constant temperature;
- High market value for products;
- No wastage of produce;
- Better bargaining power and prevention of distress selling for the farmers;
- Entrepreneurship opportunities at the rural level through value addition to fresh produce;
- Grid-independent, renewable source of energy for food storage.

CONCLUSION

PCMs have started replacing the non-standard eutectic mixtures like glycol-water in the refrigeration industry. It has also found an apt place in last/first mile delivery operations of cold chain logistics. Here, the selected PCMs in suited encapsulation forms are used to maintain the required cold temperature ranges in the insulated containers of reefer trucks used for transporting temperature snesitive products. The advantage here is, complete savings on their running/operational costs, inspite of minimal rise in initial capital investment.

With minimal changes in the existing systems, PCM could be easily integrated.In chest coolers and freezers, savings of upto 22% was achieved, while in reefer application, there is remarkable saving of atleast 40-50% by reduing running or operational cost.

In case of solar micro-cold rooms, the system is independent of grid supply. Owing to the high latent heat capacties of the selected PCMs (220-320 kJ/kg), efficiency of the systems is high. As a result efficient performance, PCM based systems have replaced the need for active cooling systems.

The economic and enviromental analysis also shows that incorporating PCM in refrigeration systems is beneficial for the end-users, national economies and for the environment globally. Different iterations and tests performed before commercializing the PCM integrated products show that the operation modes, freezer/cooler models, surface area availability, PCM packaging and the location of PCM in refrigeration cycle all play important roles in energy savings.

Refer trucks integrated with PCM ensures that the cooling system remains intact and long lasting due to its non-moving components involved. This technology ensures that the perishables and temperature sensitive consumable products are safe and secure even in a situation of breakdown. Low maintenance, no special training requirement to operate this system are some of the added advantages. Its robust and smart controls enable maintaining temperature and air quality parameters at just the right levels inside the storage volume. The very intuitive human-machine interface provides a hassle-free and an unparalleled user experience. Thus, this technology promotes the usage of clean and green energy by minimizing the dependency on use of non-renewable fossil fuel. The technology enables compact systems since PCM allows passive cooling. Installation of refrigeration system on the moving part becomes redundant. Handling is easier since the system does not demand high maintenance. Regular cleaning is the only maintenance desirable.

PCM based solar micro cold room is helping to achieve sustainable development goals (SDGs) including SDG 2 – Zero Hunger, SDG 7 – Affordable and Clean Energy and SDG 11 – Climate Action. If adopted on a large scale, such technologies will help minimize food wastage, double farmers' incomes and generate employment.

Even though the system promises an energy efficient techology, the reason of slow acceptance is; currently, there are no energy rating standards for commercial cooling units. The value proposition of temperature backup is slowly becoming redundant as the power situations are improving in both Rural and Urban India. In regions where power situation is absolutely critical i.e. needing more than 10 hours of temperature backup is a small thereby shrinking market segment.

To speed up the acceptance of this technology, a pull factor instead of pushing through the OEMs is required. A second aaproach is to encourage OEMs to develop/redevelop PCM based cooling units (Chest freezers & chest coolers). The designs should be aimed to maximize energy cost savings with minimal impact on capital cost. There is already a market for PCM based cooling units, however currently the product is designed with focus on providing backup of upto 10 -12 hours using PCM. The systems will be validated for the energy saving claims through credible bodies such as Bureau of Energy Efficiency(BEE), United Nations Industrial Development Organization(UNIDO). The end users such as retailers, hypermarkets, warehouses are looking at assets which could reduce operating costs while BEE/UNIDO's focus is on energy efficiency. Also, many of these end users receive these cooling units free from FMCG companies to store their food products. A validated published report will be instrumental for end users to demand for energy efficient cooling units.

NOMENCLATURE

PCM = Phase Change Material

TES = Thermal Energy Storage

SDG = Sustainable Development Goal

OEM = Original Equipment Manufacturer

HS = Hydrated Salt

UNIDO = United Nations Industrial Developoment Organisation

CII = Confederation of Indian Industries

GHG = Green House Gas

ACKNOWLEDGEMENT

I would like to acknowledge the support provided by UNIDO and CII teams for giving us a global platform to proove the claimed technological advantages which PCM technology imparts, specially to refrigeration industry. I would also like to extend gratitude towards all of our OEM partners (Anand Refrigeration, Icemake Refrigeration Pvt. Ltd. , Western Refrigeration, Rinac India Pvt. Ltd., Koldseal) who adopted the PCM technology at an early stage, setting up the example of taking early initiatives towards environmental conservation and end-user satisfaction parallelly.

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ROLE OF INDUSTRIAL INTERNET OF THINGS IN CREATING SMART FACTORIES

Rohit Chashta[1], Aalok A. Deshmukh[2]

[1]*Energy Efficiency*
Schneider Electric
Gurgaon, India
rohit.chashta@se.com

[2]*Energy Efficiency*
Schneider Electric
Gurgaon, India
aalok.deshmukh@se.com

ABSTRACT

Industrial Internet of Things (IIOT) is often presented as a revolution that is changing the face of industry in a profound manner. This paper starts with an introduction to IIOT and explains how, in the area of smart enterprise control, we will see self-organizing machines and assets that enable mass customization. In the realm of asset performance, the collection and analysis of data from cost-effective and intelligent sensors will improve business performance and asset uptime. A new generation of "augmented" workers will leverage cutting edge technologies, including mobile devices and augmented reality.

This paper further discusses the impact of IIOT on conventional manufacturing methodologies. Factories will have information driven architectures where operational technology (OT) will merge with information technology (IT). IIOT will also allow users to choose either a highly centralized or distributed architecture, or a hybrid approach based on their specific requirements, allowing products and machines to be connected to each other. Connected products and machines will facilitate big data analytics and a better operational monitoring and control of processes, resulting in enhanced energy and process efficiency. The paper also discusses several barriers that will need to be overcome before IIOT is widely adopted across manufacturing industries. These include the establishment of industry standards around IIoT, cyber security protection, and workforce adaptation to new sets of skills.

The paper concludes with a discussion on the practical implementation of the above concepts at Schneider Electric India's smart factory at Hyderabad.

Keywords— Industrial IOT, Smart Factory, Energy Efficiency, Digitization, Industry 4.0

INTRODUCTION

The Industrial Internet of Things (IIoT) is often presented as a revolution that is changing the face of industry in a profound manner. As the necessary global standards mature, it may well take another 15 years to realize the full potential of IIoT. Over this period of time, the changes to the industry will be significant. However, one of the challenges in understanding the potential of IIoT is the very large scope of applications. In the area of smart enterprise control, for example, we will see self organizing machines and assets that enable mass customization. In the realm of asset performance, the collection and analysis of data from increasing numbers of cost-effective and intelligent sensors will increase business performance and asset uptime. A new generation of "augmented" workers will leverage cutting edge technologies, including mobile devices and augmented reality. With easier access to information across the enterprise, their work becomes simplified and production systems grow more profitable.

The IIoT vision of the world is one where smart connected assets (the things) operate as part of a larger system or systems of systems that make up the smart manufacturing enterprise. The "things" possess varying levels of intelligent functionality, ranging from simple sensing and actuating, to control, optimization and full autonomous operation.

The smart manufacturing enterprise is made up of smart machines, plants and operations all of which have higher levels of intelligence embedded at the core. The linked systems are based on open and standard internet and cloud technologies that enable secure access to devices and information. This allows "big data" to be processed with new, advanced analytics tools and for mobile technologies to drive greater business value. This, in turn, enables improvements to efficiency and profitability, increased cyber security and innovation and better management of safety, performance with reduced CO_2 emissions impact.

EMERGING TRENDS FOR SMART FACTORIES

While the long term impact of IIoT is at times difficult to predict, three distinct operational environments have set the stage for the smart manufacturing enterprise to emerge.

Smart Enterprise Control

IIoT technologies will enable a seamless integration of smart connected machines and smart connected manufacturing assets with the wider enterprise. This will facilitate more flexible and efficient, and hence profitable manufacturing. Smart enterprise control can be viewed as a mid-to-long-term trend. It is complex to implement and will require the creation of new standards to enable the convergence of IT and OT systems.

One of the biggest potential benefits of next generation IIoT systems is the breakdown of enterprise silos. The technologies will allow for closer integration of production systems and ERP systems, Product Lifecycle Management (PLM) systems, Supply Chain Management and Customer Relationship Management (CRM) systems. Today these systems are managed somewhat independently of each other, which prohibit a holistic view of the enterprise. It is believed such a holistic approach could facilitate an enormous efficiency gain of up to 26% for enterprises (McKinsey & Company, 2015).

Smart enterprise control does not mean replacing current automation systems with completely new systems. Instead, it implies the connection of current automation systems with enterprise, lifecycle and value chain systems. This optimizes the entire manufacturing enterprise and enables a much greater degree of business control.

Seamless integration will allow enterprises to not only be more efficient, but also more profitable, thanks to greater flexibility and responsiveness to volatile market conditions. The notion of control will expand from the real-time control of a physical parameter, to the right-time control of the whole business, including both physical and non-physical parameters. Benefits will include the ability to enhance protection against cyber threats, more innovation, and the ability to better manage safety, performance and environmental impact.

Examples of smart enterprise control include the following: mass customization, reducing the size of product recalls, detection of defective products earlier in the manufacturing process and modification of product design to eliminate root causes, modification of production planning based on weather forecasts, modification of production plan/recipes based on the spot price of raw materials.

Asset Performance

Asset performance management applications such as energy management and predictive maintenance are not new to industry, but have had limited uptake due to the cost of implementation. The costs of physical connectivity (the cost of cabling to the sensors) and logical connectivity (integration with existing systems) have been prohibitive. Wireless IP connectivity and cloud-based architectures now overcome these cost barriers. In addition, a new generation of simple, small and low cost sensors is emerging; As a result, next generation IIoT systems will deliver innovative solutions in the area of asset performance.

Consider the example of condition-based monitoring/predictive maintenance. A lot of money is wasted on maintaining equipment that doesn't require maintenance, or by neglecting equipment that subsequently fails and causes unanticipated production downtime. Solutions such as condition based monitoring do exist today, but uptake has been limited by cost. Next generation IIoT systems promise to significantly reduce implementation costs for such solutions.

Augmented Operator

The use of mobile Human Machine Interface (HMI) technologies such as smartphones, tablets and wearable, combined with IP-access to data and information (analytics and augmented reality) will transform the way operators work. Portable wireless devices will expand their capabilities and technologies such as dynamic QR codes will improve the operator experience and render the "augmented" operator more productive. Today, operators only have access to information from automation systems. In the coming times, augmented operators will access information from all of the needed enterprise systems and will manage not just process performance/efficiency, but also process profitability.

IMPACT ON CONVENTIONAL MANUFACTURING METHODOLOGIES

There are three major impacts that would be seen on the conventional manufacturing methodologies.

Information Driven Architectures

As smart manufacturing enterprises start implementing smart enterprise control and asset performance systems managed by augmented operators, automation vendors will respond by implementing IIoT at all levels of the automation hierarchy. This will allow an easy integration with next generation IIoT systems. In addition, with the increasing power of embedded electronics, connected intelligence will migrate down to the lower levels of the automation hierarchy – to the control level and to the sensors and actuators. As a result, operational technology (OT) systems will merge with information technology (IT) systems and the automation hierarchy will evolve to be a much flatter and more information driven architecture. Since the future implications of this are still unclear, the technologies and architectures employed must be flexible, adaptable to change and capable of integrating with legacy systems. The monolithic, single-source, hierarchical approaches and architectures of the past will not work in the future.

Centralized Versus Distributed Control

The arguments for highly centralized redundant control systems versus highly distributed control systems have gone on for many years. Proponents of each architectures fiercely defend their position with valid arguments.

The advent of IIoT does not resolve this long-standing debate. On one hand, the use of cost-effective embedded electronics in field devices argues for more distribution of intelligence and control. On the other hand, the high speed IP-connectivity of field devices enables a more centralized architecture where all the sensors and actuators are connected to a highly redundant and powerful multi-core processor located in a secure on-premise data centre.

Today an application is programmed with a particular hardware target in mind, for example, a PLC. In the near future, an application will be programmed independently of the underlying automation hardware, and the system will distribute the application transparently to the hardware, configuring all communication mechanisms automatically. This approach will allow users to choose either a highly centralized or distributed architecture, or a hybrid approach based on their specific requirements and concerns. A Distributed Control Standard (IEC 61499) exists, that will facilitate this work and which can be used as the basis for an IIoT distributed control standard.

The distribution of intelligence into the field will allow smart connected products and smart connected machines to publish important information in a standardized format. Intelligent devices will make this information available in a transparent manner to the systems and applications that require it. This approach will overcome one of the current challenges, that the location of information is unknown and therefore cannot be discovered or exploited without custom programming.

Therefore, smart machines and devices supported by IIoT, will offer the ability of selecting a user-defined architecture.

Making Machines Smarter Through Connectivity

Machines will connect directly to the broader network, to bring the smartness aspect. This enables data sharing and production planning, which goes far beyond the capabilities of traditional standalone machinery and automation. Smart machines will bridge the information technology (IT) and operational technology (OT) gap, making available production data that can be used in numerous management settings (e.g., stock control, operator scheduling, maintenance, energy management, and product replacement). Standards to put values and parameters in a meaningful context and a common language will be a fundamental requirement for this to happen.

Another aspect of smart machines will be machine operators and factory floor engineers embracing in ever greater numbers the concept of using mobile devices at work. These devices provide operators with the flexibility to move around while still accessing machinery data, as the operators will no longer be needed in close proximity to a machine in order to monitor or manage performance. Machine engineers can also diagnose problems and offer guidance remotely, which speeds up implementation of a solution. This reduces downtime and losses from component failure (Conway, 2017).

ENHANCED ENERGY EFFICIENCY THROUGH IIOT

Industrial IoT applications positively affect factory performance and energy efficiency with improved insights and action points through monitoring and

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analysis of energy data. As data are delivered real-time on a single central dashboard interface, operators have the convenience of sorting and filtering these. The energy efficiency outcomes achieved during interactions between hardware and devices become better, which results in developing more advanced operational profiles. Digital automation becomes possible and quite feasible as powerful IoT connected sensors get smart enough to use power only when they need and consume less energy in its dormant mode. In addition, it is easier to watch out for system malfunctioning or to know when they go through low-efficiency phases so that serious issues can be addressed a lot faster. Advanced data analytics powered through IIoT, also enables predictive and forecasting capabilities for energy use, and co-relates it with factors like production, machine running hours, employee working hours, etc. to give an accurate operational energy efficiency profile of the factory or the process, and thus, enabling the factory operator to plug the low efficiency gaps.

With increased installation of smart devices like actuators and valves embedded with sensors, better monitoring and control features like predictive maintenance and fault or breakdown alerts, can also be enabled, resulting in a better operational reliability (Beudert, et al., 2016).

IIoT also enables the implementation of energy efficiency concepts and approaches like M&V 2.0 and MBCx (monitoring based commissioning).

M&V 2.0

M&V 2.0 is an approach to provide new tools and technology with a potential to reduce the cost of conventional M&V and produce more timely results with higher levels of confidence, transparency, and accuracy. It introduces new software and energy data communication technologies and measurement approaches to enhance the way M&V is carried out. Advances in software, cloud computing, and large-scale data processing powered by IoT, are enabling these approaches, that provide for the continuous measurement of energy savings. Today, along the lines of IIoT, there are three major enablers for this approach of advanced M&V:

- Advanced Data Analytics - With a growing range of cloud-based software and platforms that process large volumes of data efficiently, advanced data analytics present opportunities for M&V 2.0 programs by analysing the higher volumes of data collected and using statistical models on large historical data to forecast the future energy consumption. Through advanced data analytic tools, billions of data points of disparate data can be processed within seconds or minutes. In M&V programs, high-speed analytics and machine learning can identify these patterns and provide good prospects for data cleaning, detection of patterns and variances, and developing forecasted energy use.
- Using Software as a Service (SaaS) - Using SaaS, along with advanced metering infrastructure (AMI) and analytics, M&V can be automated and energy savings, as the difference between the adjusted baseline and metered consumption, can be reported in near-real-time. Automated M&V and SaaS can be used as a combination for conducting energy audits, tracking and benchmarking of projects, doing virtual energy assessments, and project planning and optimization.
- Improved Data Collection Tools – This is one of the most important aspects that IoT has enabled, i.e. the smart instrumentation and improved data collection tools. With advancements in instrumentation to collect enhanced data, some of the tools that can play an important role in implementing the concept of M&V 2.0 are smart meters and advanced metering infrastructure (AMI), smart sensors, controls and home energy management system (HEMS), and non-intrusive load monitoring (NILM) tools.

Monitoring Based Comissioning (MBCx)

Another approach to energy efficiency that can be and is facilitated by IIoT is monitoring based comissioning. MBCx emphasizes continuous performance monitoring and trending for diagnosis of energy wastage, for savings accounting, and to enable persistence of savings. It has emerged as a paradigm shift for owners and operators of large buildings and the commissioning industry that serves them. MBCx tools leverage manual remote monitoring services or advanced analytics engines to continuously diagnose facility performance and identify equipment and system faults, sequence of operations improvements, and trends in system and energy use. These consistently help the facility staff maintain a facility's performance at desired levels over time. Furthermore, monitoring and analysis is also used to help ensure the persistence of savings by alerting facility staff and management to degradation in performance and to detect faults in operation. MBCx based techniques and tools can significantly reduce the time, effort and level of knowledge required to acquire and analyse data to reveal energy-consuming operational faults, such as failed sensors and controllers, poorly implemented schedules, improper operations, idle running of production lines, and valves leakages.

Also, tools and technologies like a building management system (BMS), which is mainly used for on-site management and control of HVAC, lighting, fire, and safety and security systems, integrated along with an energy management system (EMS), that has the capability to provide analytics for energy use, demand, and power quality; can be used to continuously monitor and control equipment and systems during operations.

CHALLENGES IN ADOPTION OF IIOT

Several barriers will need to be overcome before next generation IIoT systems are widely adopted across manufacturing industries. These include the establishment of industry standards around IIoT, cyber security protection, and workforce adaptation to new sets of skills.

Standardization

Standards are required to allow smart connected products, machines and assets to interact in a transparent fashion. This goes beyond the simple communication protocols, and involves the creation of standard semantics and mechanisms that will allow smart devices to discover each other and interoperate. Some standards, such as PackML, do exist in this area, but they are incomplete and do not cover all aspects of manufacturing. The Industry 4.0 and the Industrial Internet Consortium initiatives are currently addressing this matter of standardization.

Cyber Security

The advent of the IIoT is accelerating the need for cyber security in industrial control systems. The complexity of IIoT will mean that cyber security must be designed into the components that make up the automation system. The adoption of industrial security standards with certification will be essential to the advancement of IIoT because it will ensure the security not just of individual assets but also of the larger systems and systems of systems. These will play a role similar to those which occur in the realm of safety certifications. Adherence to the certification means that the elements of a system hold the key security building blocks. The elements are combined in a secure way by security certified teams and are operated as a secure system by security trained operators.

The key to security certification is consistency and applicability. Worldwide, the IEC62443 series of security standards covers all elements of security from product development through to product features, system features, delivery and operation. It is important to note that while today some independent bodies offer certification to IEC62443, IEC itself has not yet endorsed any of these bodies for IEC62443 certification.

Complementary to IEC62443 security standards, existing industrial standards are also evolving to be more secure. DNP3 has evolved to DNPV5 to add security, OPCUA offers significant security enhancements, Modbus is evolving to Modbus Secure, and EtherNET/IP is becoming EtherNET/IP Secure. In addition many IIoT systems are adopting security features derived from existing IT standards such as HTTPS, certificates, and encrypted/authenticated protocols.

Worker Competencies

The skill-sets required to design and operate an IIoT based system are somewhat different from those needed to run a classical automation system. A significant amount of re-training will be required for existing operators and maintenance staff to manage such systems. The good news is that the IIoT systems will use technologies that are familiar in everyday life, and the new generation of young operators will have no problems adapting to this new approach. The main challenge for automation suppliers will be to design and supply diagnostics/debugging tools that can rapidly identify the root cause of problems. This will ensure that a malfunctioning or downed system can be restored quickly.

INDIA SCENARIO: MOVING TO SMART FACTORIES / INDUSTRY 4.0

Globally, the Industry 4.0 market is expected to reach INR 13.9 trillion by 2023 (Business Insider, 2018). Countries such as the US, China, and Japan and European nations such as the UK, Ireland, Sweden and Austria have all started adopting Industry 4.0 or smart manufacturing.

Current Status In India

The manufacturing sector forms an integral part of our country’s long-term vision; as seen by the government’s strong focus on the ‘Make in India’ campaign.

Industry 4.0, powered by IIoT, presents a great opportunity for India to realise its manufacturing ambitions. At present, India lags its global peers in adoption of smart manufacturing technologies. A significant portion of the Indian manufacturing sector is still in the post-electrification phase, with use of technology limited to systems that function independently of each other. The integration of physical systems on cyber platforms, the basic premise of IIoT, is still in its infancy. Furthermore, the Micro, Small & Medium Enterprises (MSME) segment has very little access to technology due to the high cost barrier.

Key challenges: Following are some of the key challenges that our country is facing in our shift towards IIoT and Industry 4.0 approaches:

- Lack of adequate infrastructure (physical and digital) – despite continuous effort of the government, India still lacks telecommunication network infrastructure, and the existing one still suffers from low data speeds and unstable connections.
- Cyber Security - According to KPMG's survey, India Cybercrime Report 2017, 79 per cent of corporations in India have acknowledged cyber security as one of the top-five business risks. Apart from cyber security, the regulatory environment pertaining to data privacy also needs to be strengthened
- High initial cost of digital technologies – Building the factory of the future and having an entirely connected system could require significant capital outlay. Getting access to digital technologies for MSMEs, that form the base of Indian manufacturing sector, remains a challenge due to the high cost of these technologies.
- Workforce competency or skill gap – India's current workforce lacks skill and expertise in newage technologies such as data analytics, additive manufacturing, and IoT. Government, industry and academia need to collaborate to enable an Industry 4.0 ready workforce.

Drivers

The government aims to augment the share of manufacturing in GDP to 25 per cent from the current 17 per cent, by 2022. In 2015, the Indian government launched an IoT Policy that aimed at skill development, technological upgrades, and building IoT products specific to Indian demands, thereby occupying a considerable share in the global IoT market. In addition, the government is formulating a National Policy for Advanced Manufacturing to enhance India's global manufacturing competitiveness. The government has recently announced the launch of a mission on Cyber–Physical Systems (CPS) and allotted an initial corpus of INR100 crore for commencement. Once fully implemented, these plans would be key tools to enhance the contribution of manufacturing output.

Going by the progress that India is seeing in the two very critical enabling Industry 4.0 technologies, IoT and big data, the country seems to be developing the right platform to base its 'smart factories'. India is expected to command nearly 20 per cent of the global IoT market, which is estimated to reach INR19,49,505 crore by 2020 (IOT India, 2016). Furthermore, IIoT, or the segment of the IoT market that particularly caters to the manufacturing sector, currently accounts for 60 per cent of the Indian IoT market. The big data analytics market in India is currently valued at INR12,997 crore and is expected to grow at a CAGR of 26 percent reaching approximately INR1,03,974 crore by 2025, making India's share approximately 32 percent in the overall global market (Nishimura, n.d.).

Opportunities And Way Forward

Going forward, Industry 4.0 can transform the Indian manufacturing sector. However, this change would require collaborative effort from various key stakeholders, including the government, corporate, manufacturing, and IT sectors, for putting a viable ecosystem in place.

Industry 4.0 and smart manufacturing factories can provide benefits such as cost reduction, higher efficiencies, safer factories and faster speed to market, It can also provide the country's manufacturing sector the much-needed platform to stay competitive in the global market.

Automative (with collaborative robots), textile (with intelligent plant framework), and packaging (with connected machines) are the prominent sectors to adopt the concepts of IIoT and Industry 4.0.

CASE STUDY – SCHNEIDER ELECTRIC HYDERABAD SMART FACTORY

Schneider Electric (SE), in the year 2018, transformed its Hyderabad factory in to a smart factory, which is aligned with the organization's global initiative to transform 100 of its factories to smart factories by the year 2020. The SE Hyderabad factory showcases the role of digitization and IIoT in improving a variety of its processes.

The demo zones at the facility help visitors experience how automation and internet of things function in an industrial environment, and how the entire process could be remotely controlled and managed through a hand-held tab or device. In the Hyderabad smart factory, various technologies, including artificial intelligence, robotics, analytics, big data and internet of things, are all laced together as a single connected entity to facilitate automation. Following is a snapshot of various digital and IIoT powered technologies implemented at the Hyderabad smart factory:

- Schneider Electric Production System: is a digital system for lean manufacturing methods and tools that empowers the facility team and improve customer experience and end-to-end operational efficiency. A digital platform for material procurement and delivery of services to the customer with end-to-end digital planning and control are some of the accelerators for this initiative.
- Digitized and smart factory operations: The Hyderabad factory is completely equiped with digital solutions like software for Manufacturing Execution System (MES), Efficiency Equipment Advisor, Augmented Operator (a solution that works on augmented reality application and used for maintenance check and fault rectification), Automatic Guided Vehicles (AGV) powered by robotics application, 3D printing with virtual reality applications, and smart data collection tools like sensors and advanced meters for energy analytics, load forecasting, and predictive maintenance.

With the implementation of all the above measures, and the transformation of the Hyderabad factory to a smart factory, in FY 2018-19, the plant was able to avoid 8.5% of its energy use, in comparison to the FY 2017-18 baseline. It is worth noting here that by the year 2017, the Hyderabad plant had already avoided energy use to the tune of about 20% in comparison to the 2011 baseline. This demonstrates how transformation to a smart factory, powered by IIoT applications, has helped a plant that was already 20% more efficient than it was six years ago, to improve its efficiency further by 8.5%.

CONCLUSION

The trends in new and advanced industrial tools and technology, powered by IoT, hold great potential for effective energy management, optimization, and improved processes by the use of Industry 4.0 approaches. Although emerging technologies with regards to software, hardware, and data availability are still evolving; the new tools and methods will enhance monitoring, analysis, and a complete end-to-end control of various manufacturing processes. Overall, the role of IIoT in the changing paradigm of industrial processes is extremely critical. This paper also discusses the current Indian scenario, potential, challenges, opportunities, and the way forward. Lastly, the paper concludes with a case study on Schneider Electric Hyderabad smart factory, which demonstrates the actual implementation of these concepts in a live manufacturing setting.

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ENERGY OPTIMIZATION AND OPERATIONAL TRANSFORMATION IN THE QUICK SERVICE RESTAURANT SEGMENT THROUGH IOT-ENABLED BIG DATA ANALYTICS

Amiya Ranjan Behera[1], Ashish Jain[1], Baburaj Kaimalilputhenpura Prabha[1], HAPS Dhillon[1]

[1]*EcoEnergy Insights, India*

ABSTRACT

The Quick Service Restaurant (QSR) segment is one of the fastest evolving and competitive segments in the food industry (Digbijaya Ghale, 2017). In this segment, it is important for each brand to enhance its customers' comfort and satisfaction – these being strongly associated with food quality, ambiance and service provided. Our research focuses on the day-to-day challenges encountered in this segment, like high fluctuation in energy usage, frequent equipment breakdown, lack of timely maintenance and procurement of energy-efficient equipment. We also focus on how the adoption of technological innovation around the Internet of Things (IoT)-enabled Big Data analytics has transformed the QSR segment.

This paper covers different use cases of the analytics-driven digital transformation of restaurants, such as energy efficiency, occupant comfort, proactive fault detection, and remote diagnostics, food safety compliance, condition-based maintenance, air quality improvement, performance assurance, and equipment lifecycle enhancement. While data-driven advanced analytics enhances the overall customer experience in the "Front of House" (FOH), it facilitates better visibility into the QSR business in the "Back of House" (BOH) through data normalization, data modelling, strategy customization, prioritization of derived actions and persistence validation. In the competitive QSR landscape, food quality and service uniformity will always remain the standard of success. IoT-enabled Big Data analytics platforms will effectively aid QSRs in achieving those target standards while improving operational efficiency and driving business growth.

Keywords — Measurement & Verification (M&V), Energy Utilization Index (EUI), Energy Management System (EMS), Service Window concept, Food Safety, Equipment health, Building Management System (BMS), Quick Service Restaurant (QSR)

INTRODUCTION

A Quick Service Restaurant (QSR) creates an alternative choice for customers by combining the accessibility of fast food with the quality of casual dining. QSR is one of the most dynamic segments in the food industry. The QSR industry faces a number of specialized challenges starting from growing food and energy cost, compliance concerns over food safety, operational inefficiency, fulfilling continuously changing guest expectations, etc. To control costs and avoid food wastage, it is critical for them to optimize their inventory and supply chains. Marketing campaigns and promotions can handle only a few of these challenges merely for a short period of time. To be an elevated participant in the QSR market and witness long term progress, operators need to adopt integrated technology i.e. internet of things (IoT) and data-driven insights to anticipate the ongoing challenges, streamline operations, improve the overall efficiency and profitability. Data-driven applications enable the operators to analyze, understand, and act upon massive amounts of data related to consumers, operations, food safety, and equipment health. Nowadays consumers are busy and more health-conscious. They look for nutritious and budget-friendly options. To cater to this challenge, the QSRs have to diversify their menus to offer healthier options based on market data analytics.

QSRs are evolving constantly by the data-driven digital technology transformation. On the front of the house, digital platforms have gained momentum by supporting online food ordering and electronic payment. Similarly, at the back of the house, IoT based building management solutions are enabling the QSR industry to achieve improved profitability by continuously monitoring and optimizing operations. This involves the operation of heating ventilation and air conditioning (HVAC), refrigeration units, lighting, and kitchen equipment. These solutions use a cloud-hosted data analytics platform for remote monitoring of critical equipment and energy-intensive devices. This analytics platform lowers the maintenance cost by reporting performance to identify and send alerts along with actions to resolve issues proactively. These platform-driven solutions can offer benefits such as improving guest experience, making operational processes more efficient and enabling a proactive approach towards food safety. Here the research is focused on how an analytics platform is becoming a game-changer for the QSR industry with examples of different case studies.

The digital transformation revolution is enabling the QSR industry to evolve rapidly. However, the benefits and return on investment of data-driven technology solutions are often précised through insubstantial results, such as guest satisfaction, which are hard to measure and even harder to quantitatively associate (Fliss, Accounts and Global, 2020). The market research says, ideally the restaurants are more focused on profit and contribute less priority in investments for new innovative technologies and instead they prefer to wait-and-watch approach, investing once a solution is tried and tested (Digbijaya Ghale, 2017). This type of initial disinclination is reasonable because technology integration and training the staff to equip them with the skills is often time and cost concentrated for top management. There is always a learning curve to be accounted for, and initial hiccups can be a big distraction for the restaurant chain's core problems and challenges. Additionally, in some instances, process efficiency cannot be completely solved through the implementation of data-driven technology (microstrategy.com, no date). In such cases, inherently incompetent processes need to be replaced with an efficient one.

Another frequent challenge is the lack of awareness of operator and facility managers to different analytics platforms and the benefits they offer. It is very hard to map the tangible benefits on the company's bottom line to the technological investments done by the operator (Sinha, 2015). This generally drives the operator to not appreciate the value of the technology. For instance, a decrease in the electric utility bill cannot be fully accredited to the proactive maintenance based on analytics insights and smarter controllers installed for HVAC units. There are numerous other factors such as seasonality, that could affect the consumption and billing, which means verification and validation may take time.

There is fair competition in the intensifying data-driven IoT solution to cover the QSR industry. Often, technology and applications are not being utilized to their full potential by the operator. This leads to a challenge in justifying the appropriate payback of the capital investments associated with the technologies for the QSR operators. Analytics can be fully utilized to optimize the business operation and an optimal return on investment can be realized with smooth interconnectivity and data interoperability.

TECHNOLOGY & PROCESS

Figure 1 represents an approach to the digital transformation of a QSR chain through different layers of technology and processes. The first step this of the process includes data enablement at sites by installing different IoT edge devices and sensors to connect to multiple data points and collect data such as energy usage, temperature, relative humidity, occupancy, operation status, etc. and transfer it to the cloud-hosted platform. In the next step, the analytics platform in the cloud generates actionable intelligence by adding multi-layer validation of persistence, contextualization, normalization, and prioritization.

EcoEnergy Insights set up an Operations Center to act out the intelligence from the platform. The operations center is a team of skilled analysts, data scientists and domain experts who monitor and remotely diagnose identified issues to enhance comfort, improve equipment health and increase the overall efficiency. The center is located in one center in a country and operates remotely to the restaurant network. Big Data analytics helps the operations center to diagnose issues and identify root causes through validation of the persistence of problems. The operations center resolves issues remotely by deviation prioritization, strategy customization, and continuous optimization. As a result of which, the IoT enabled advanced analytics supports the QSR industry to operate, remotely monitor and control tedious tasks without human dependency, which safeguards quality consistency, efficient operation, food safety, and cost optimization. The command center ensures minimal downtime of equipment through shorter response times and resolution times. This practice encourages top management to remain focus on improving the consumer experience, business growth and differentiating their QSR brand from the competition.

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Figure 1: Steps involved in IoT enabled Big Data analytics to derive actionable insights

AN APPROACH & PRACTICE

Digital transformation in the QSR industry can majorly be categorized into the following: a)energy-saving through schedule optimization, b)use of service window concept to identify optimization opportunities, c)equipment health monitoring, d)thermal compliance, e)equipment maintenance management, f)hazard analysis and g)critical control point (HACCP) compliance. Within these categories, there are additional segments that target improvements specific to the QSR industry. QSR operators may not target all the areas, and so typically the solution provider initially targets the key organizational challenges and prioritizes them. QSR operations challenges can be attributed to a single or combination of the following categories, which present a reason to pursue a committed solution partner. Figure 2 represents the key impact areas of using this approach in the QSR industry.

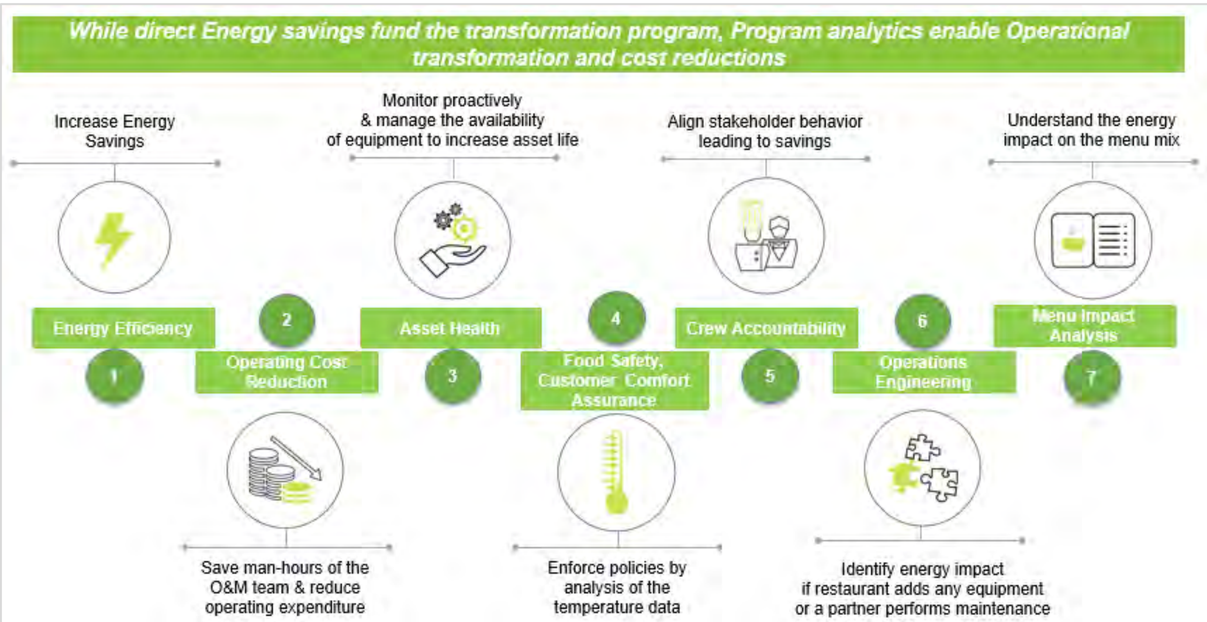

Figure 2: Operation transformation impact areas in QSR industries

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Service Window Concept

A utility bill represents the aggregated energy usage across a particular period. Therefore the overall consumption from the utility bill does not support the restaurant operator in interpreting the energy leakages to justify the saving opportunities. Even by tracking the daily basis energy usage it will be challenging to identify the concealed saving opportunities. This is because the QSR segment's consumption pattern varies throughout the day with respect to the operation type. One of the most efficient ways to understand the restaurant consumption pattern is to segregate a whole day into the service window level with respect to the operation type. The Service window concept (Har Amrit Pal Singh Dhillon, (IN); Parminder Singh and Dinesh Kumar Pathak, 2019) enables us to identify the relationship between energy consumption patterns (measured in kWh) and operations patterns, measured by site usage pattern (e.g. customer usage vs employee-only usage hours), guest count or footfalls etc. The framework illustrates unique energy and business profiles that a typical enterprise goes through, during its operations over a period of time (usually 24 hours). The profiles for each of the Service Windows are different and are usually consistently repeated every day. Using this framework, we analyze the patterns and identify the potential to save energy costs for enterprises.

As shown in Figure 3, the service windows of a restaurant are clearly detectable and classifiable which follows a repeated energy usage pattern every day. The service windows can be classified as the crew set up, crew shut down, pre-lunch hour, peak lunch hour, peak dinner, lean hour, etc. It will vary with respect to food and outlet type. Service window wise energy consumption pattern varies due to different parameters e.g. restaurant footfall, outdoor temperature, equipment usage, menu type, etc.

The service window concept helps restaurant operators regulate energy usage based on business intensity. Figure 3, represents a time series analysis of sales Vs energy usage during nine different service window in a quick-service restaurant.

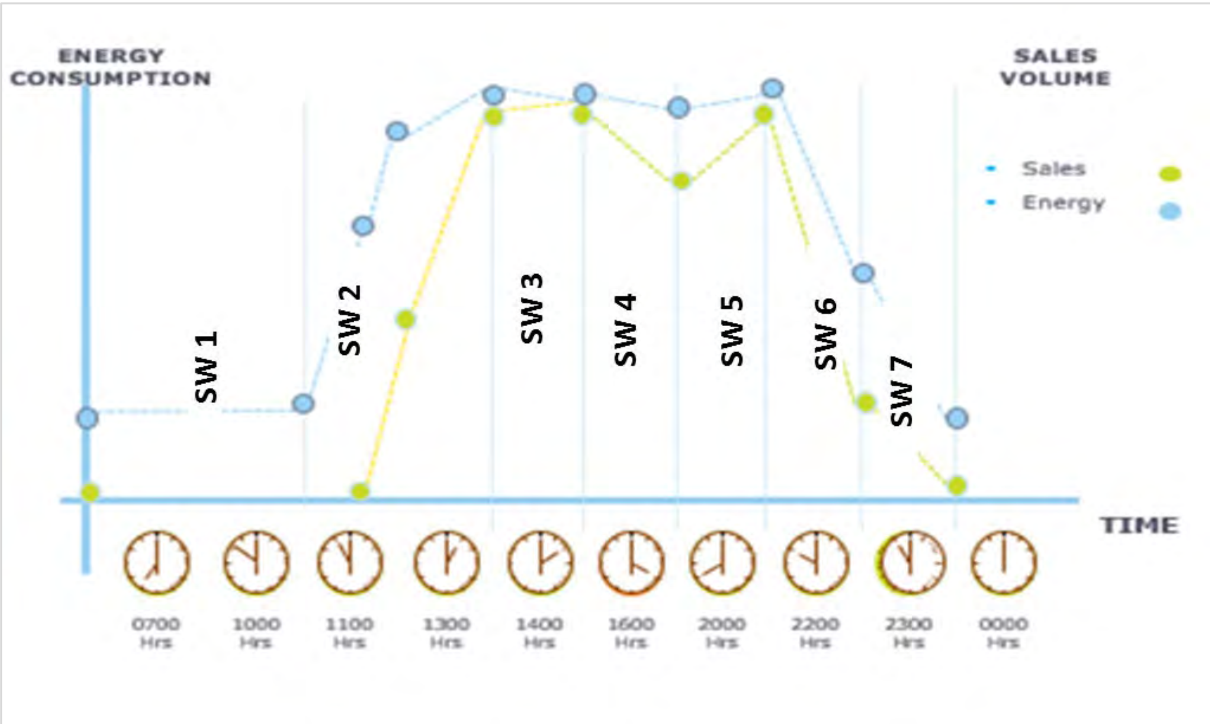

Figure 3: Segregation of QSR operation hour into multiple service window

Figure 4 represents the energy usage pattern of a typical pizza maker throughout the day segregated into different service windows. It can be clearly observed that during the business service windows, the consumption is higher and this is directly linked with guest footfall and received orders. During non-business hours the consumption pattern does not fluctuate much. With respect to different identified service window, the energy-saving strategies can be designed and implemented by set point tweaking, operation streamlining, cutting down ideal equipment run to bring down the baseline energy usage of the restaurant by 4~5% (Dhillon, Ramachandran and Singh, 2013)

Energy Efficiency

Energy-intensive kitchen equipment, heating and cooling appliances running continuously significantly adds to electricity and gas bills and increases the QSR industry's carbon footprint.

In the United States per square feet, the energy consumption of QSRs is more than any other building (Koranne and Borgave, 2017). QSR operators with a large number of restaurants often find it challenging to compare the consumption across all their stores and identify the key opportunity areas where they can focus dedicated effort to generate savings. However, IoT powered Big Data analytics enables the restaurant wise performance tracking and peer to peer energy consumption comparison to identify improvement areas by data normalization, deviation prioritization, and strategy customization. Smart electric meters can provide logs on peak demand times, which can be further processed to optimize the operation schedule of key equipment without affecting restaurant service. The climate zone, operation schedule, floor area, equipment load, restaurant age, menu, etc. are the key factors that impact energy consumption. The best-suited method to analyze energy wastage is to cluster the restaurants based on area and service window wise consumption.

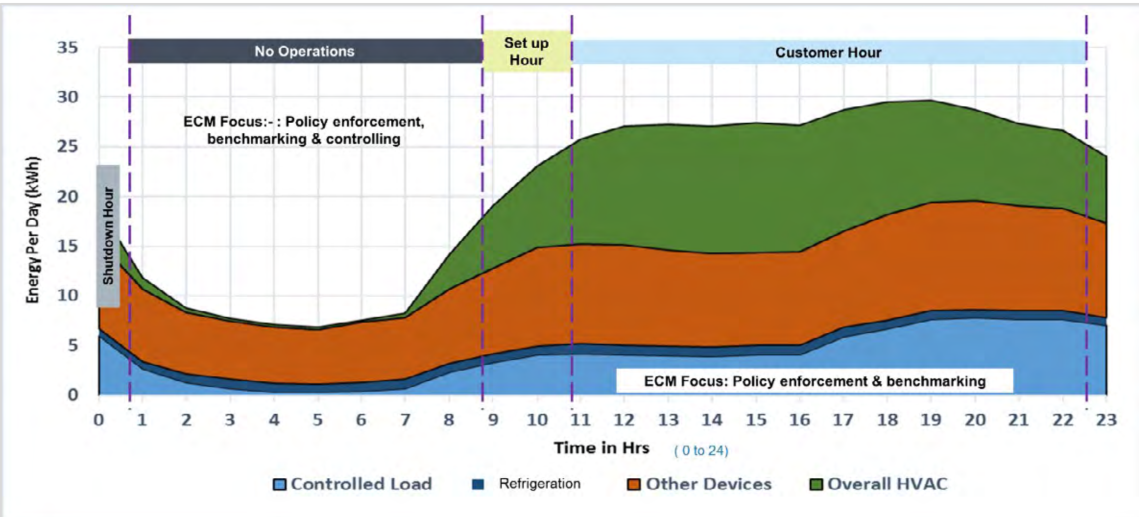

Figure 4: Typical Pizza maker Energy consumption profile

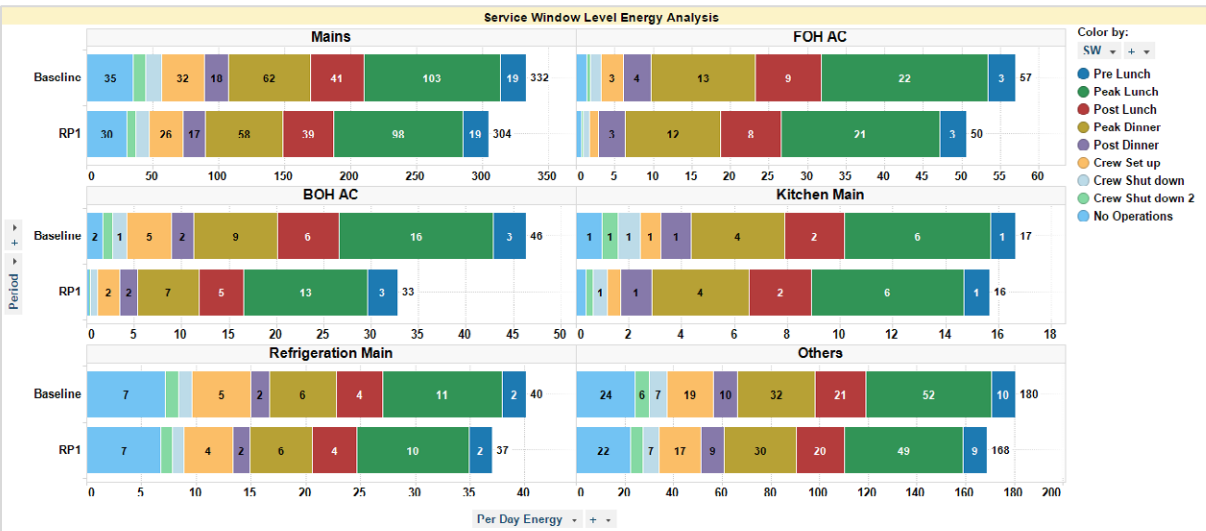

Figure 5: Energy consumption pattern and saving opportunities post ECM implementation

Figure 5 demonstrates a significant reduction in energy consumption after the implementation of different energy conservation measures for a particular QSR operator in India. The period before the implementation of ECMs (energy conservation measures) is known as the baseline period. RP1 represents the first reporting period, the immediate period after the baselining period. ECMs for energy efficiency include schedule optimization of equipment, replacement of energy inefficient equipment and reduction in energy wastage during non-business hours.

From Figure 5, it can be clearly observed that the energy wastage has been trimmed down in each load type and in each service window during RP1 as an impact of ECM implementation and this is leading to the total energy savings.

Guest Comfort analysis

Guest area temperature is one of the most crucial parameters in the QSR business as it has a direct impact on customer comfort. Guest volume, AC temperature setpoint, frequent door opening are a few of the major factors that cause temperature compliance deviations in the dining area. However, this deviation can be gradually reduced by continuous monitoring and remote controlling of AC units based on zone temperature feedback. The guest comfort is being monitored continuously by the temperature sensors installed in the dining area which pull the actual temperature at a granular level and later it is being compared against the compliance standard. Big Data analytics helps in evaluating deviations and advises the corrective actions to the restaurant operator by normalizing and contextualizing the raw data with respect to service window type, compliance range, and climatic zone.

Figure 6 represents a typical example of guest comfort analysis on enterprise-level as well as store level which helps the restaurant operator to understand the present compliance and deviation status. Reduction in undercooling will lead to an improvement in guest satisfaction and reduction in overcooling will help in saving energy. These analytical insights enable operators to train the staff to ensure improvement in customer comfort and energy-efficient operation.

Food safety analysis (HACCP regulation)

Temperature controlled inventory is highly prone to damage from door indiscipline(improper and untimely closing of doors), compressor malfunction or power interruptions. IoT driven Big Data analytics can help in remote monitoring, reduction in food wastage, compliance improvement, auto deviation detection and increase in operational efficiency. The thermal condition has to be monitored closely to provide insights remotely through the cloud-hosted platform and offer proactive actions for maintenance and alerts for unexpected deviations such as door indiscipline, wrong temperature setpoint, etc. Cloud-hosted automated data analytics eliminates human error and improves food safety.

HACCP Stands for Hazard Analysis and Critical Control Point (Food, Programs and Nutrition, no date). HACCP is an internationally recognized system for reducing the risk of safety hazards in food. Figure 7 demonstrates the deviation based on the HACCP standard for cold storage in the QSR industry. The analytics here is focused on identifying the food quality and reduce the food wastage by improving storage compliance as per the standard.

Figure 6: Guest comfort analysis w.r.t. dining area zone temperature

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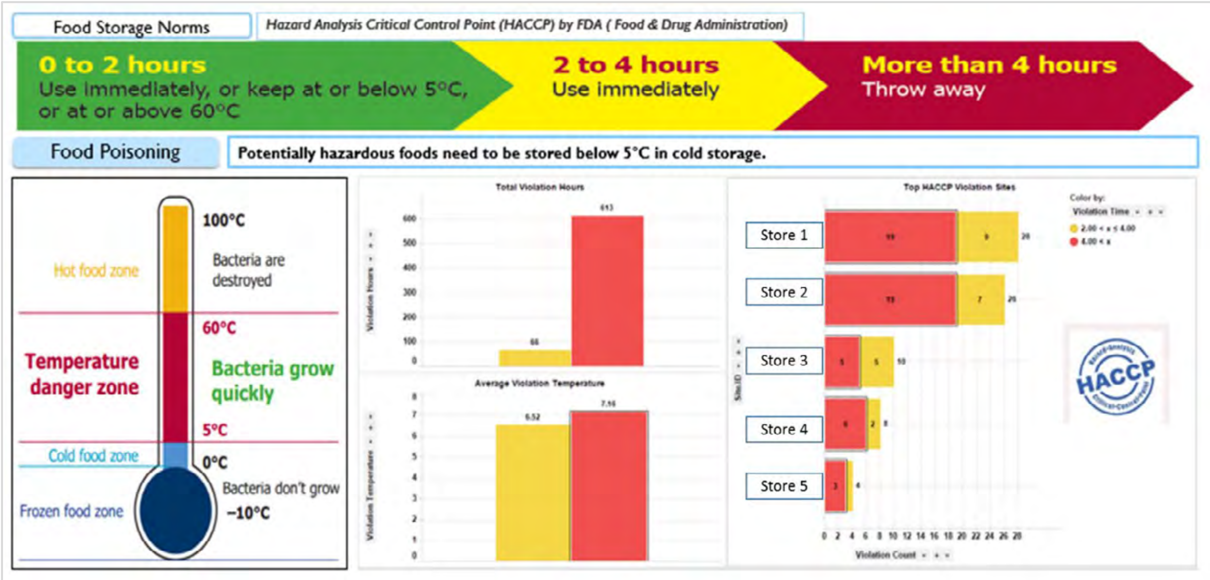

Figure 7: Food safety compliance analysis

These food safety analytics insights help the operators to identify recurrent deviations and the root cause to take corrective actions to improve the food quality.

Figure 8 shows the compliance of inventories (Walk-In Chiller) of different stores for a QSR segment in a particular period. The compliance percentage represents maintaining the critical control limits and 'WIF degree F' represents the health status of the equipment with respect to the defined acceptable temperature range. The analytics here also identifies the door indiscipline with respect to the time period. This type of analytics helps an operator understand the root cause of food wastage along with supporting his decision to streamline the inventory operation guidelines.

Equipment health analysis & Maintenance management

Remote monitoring of restaurant equipment with real-time information increases the visibility which allows proactive maintenance and reduction in service calls. The data analytics platform increases the capability using connected controls and sensors for the restaurants, which provides reliable and accurate data ensuring equipment health. IoT driven Big Data analytics helps in technical issue diagnosis, sending deviation alerts to field technicians, advising troubleshooting steps for equipment in restaurants like air conditioning units, coffee machine, oven, walk-in freezer, etc. Restaurant operators get proactive alerts that reduce equipment downtime. Equipment health

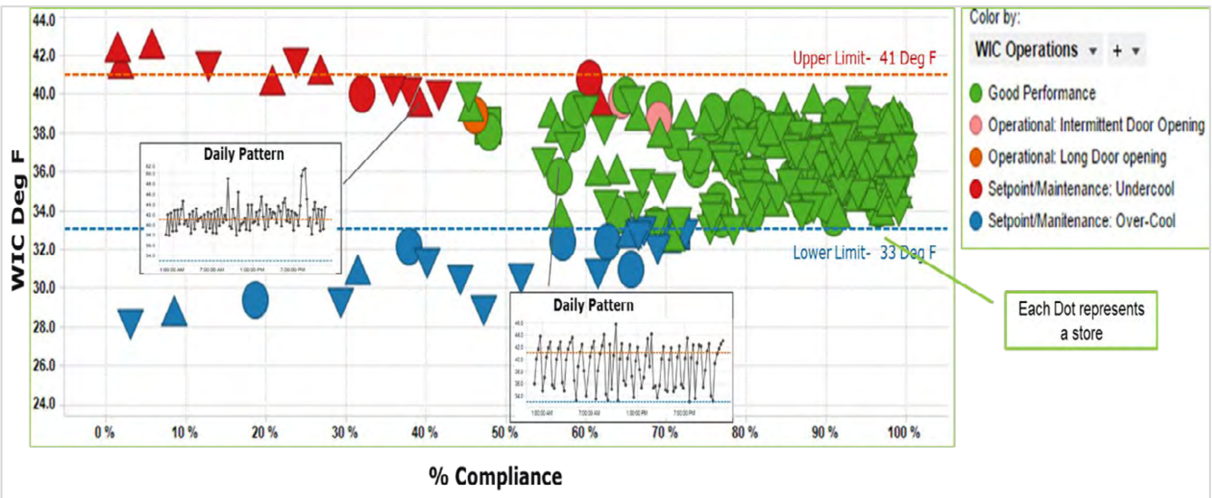

Figure 8: Food safety and inventory operation tracking

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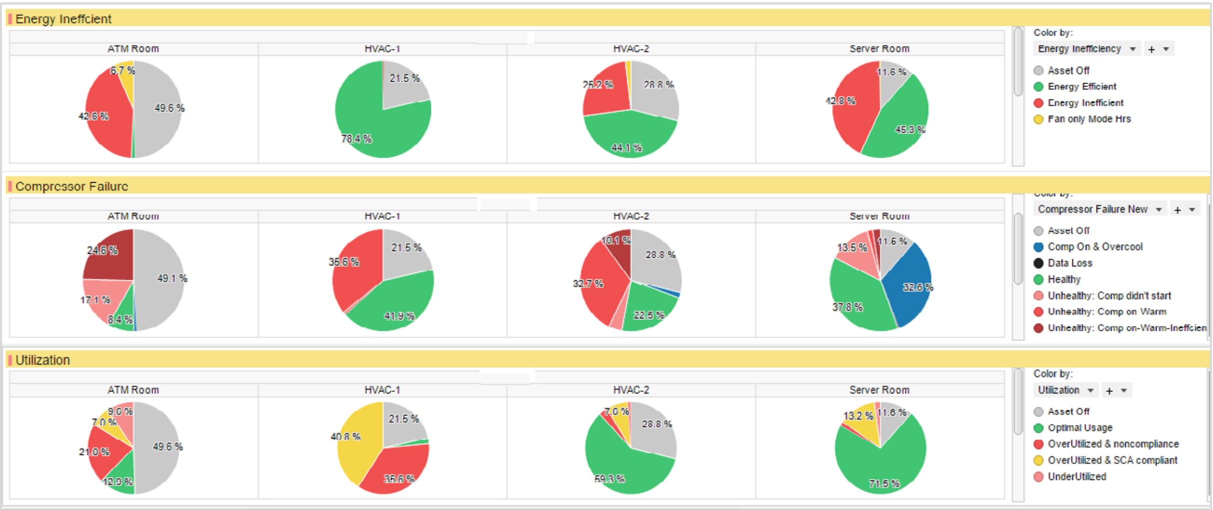

Figure 9: Enterprise-level equipment health analysis

analysis and proactive maintenance allows for the smooth operation of equipment and lessens the stress and headache of equipment breakdown during peak business hours. The integration of equipment and gaining operational insights through Big Data analytics can help grow the QSR business.

Figure 9 represents the enterprise level equipment

health analysis of a QSR operator. This analytics gives an overall equipment health status with respect to efficiency, utilization and equipment subpart performance. A QSR operator can easily identify the critical stores where he needs to be focused on these insights. In the next level, the analytics help in diving into the equipment level view of the identified restaurant to identify the unhealthy equipment and conduct the root cause analysis. In the future, these learnings from analytics-driven insights can help QSR operators in new equipment procurement decisions as well.

Implementation & Future Scope

The technology, solution and use cases discussed in this paper exhibit the capability of IoT driven Big Data analytics and how it helps QSR operators by increasing energy efficiency, operation optimization, proactive maintenance, and food safety. The QSR industry needs to quickly integrate this technology-driven solution to achieve goals such as improved energy efficiency, food safety, improved equipment maintenance management, and improved brand equity. These outcomes are crucial to ensuring QSRs stay competitive in an increasingly competitive industry, and they can perform so without impacting their bottom line. The QSR industry can benefit from adopting self-sustaining data-driven analytics insights into their business operations to ensure a sustainable future.

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POWER SUPPLY QUALITY IMPROVEMENT OF PERMANENT MAGNET BRUSH-LESS DC MOTOR

Saurabh Manglik[1], Anish Garg[2]

[1] *Jacobs Engineering India Pvt Ltd*
Gurugram, India
skmanglik.iitd@gmail.com

[2]*Delhi Transco Ltd*
Delhi, India
garganish@gmail.com

ABSTRACT

Residential household appliance consumption is one of the highest electricity consumption sector, out of which ceiling fan is second largest power consumption device in the home. This paper provides description of proposed ceiling fan and Goverenment policies to encourage manufacture and use of energy efficient ceiling fans This paper presents a new design development of the Permanent magnet Brushless DC Motor (PMBLDCM) to reduce the power consumption and reduce the harmonic distortions in the power supply, as compared to the market available PMBLDCM fans.

Further this paper summarizes the future road map to enhance the use of the Energy efficient Fans for household application with improved power quality design concepts.

***Keywords—Permanent Magnet Brushless DC Motor** (PMBLDCM)**, Buck-Boost Converter, Diode Bridge Rectifier** (DBR),**Voltage Source Inverter** (VSI), **Discontinuous Current Mode** (DCM), **Power Factor Correction** (PFC), **and Digital Signal Processor** (DSP)*

INTRODUCTION

Increase in energy demand every year encourages energy planners & policy makers to promote energy efficient appliance at micro to macro level instead of increasing power generation, which in itself has its own limitaions; apart from requiremnt of huge Capital Invetsment. In the past year, India recorded a huge demand of electricity in various consumption categories such as commercial, industrial, residential, agricultural and traction. Residential sector consumption recorded huge demand of 24.20% during fiscal year 2017-2018[1,2]. The Residential consumption includes refrigerators, air conditioners, washing machines, fans, TVs, water heaters, fluorescent tubes, and incandescent bulbs. Fan is the second largest power consumption in the home, which was recorded through survey of report of various metro cities[3]. Average all India appliance ownership of ceiling fan is 72% as shown in **Figure 1**.

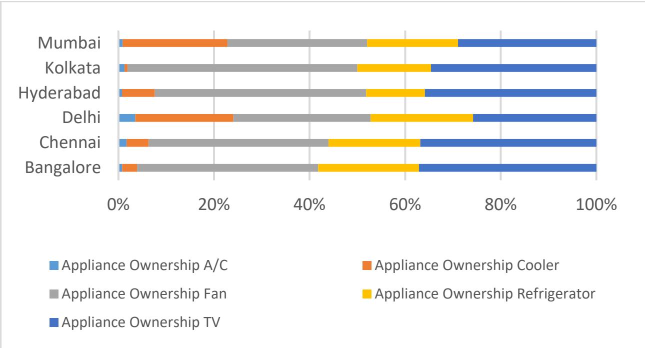

Figure 1: Appliance ownership in major metro cities of India

Even globally ownership of Fan is a major percentage. Conventional ceiling fan designed with Single phase Induction motor consume about 70-80 W, which is the major chunk of the energy demand in the residential sector.

Therefore, recently in the era of appliances of low power consumption application goods, these are more in demand and are also subsided by government policies. This paper presents modification and design of improved PMBLDCM

(Permanent Magnet Brushless DC motor) for ceiling fan with improvement of Energy consumptions and power quality in comparison with market product.

GOVERNMENT POLICIES OF ENERGY EFFICIENT FANS

Government of India has been promoting the use of energy efficient appliances with Bureau of Energy Efficient (BEE). BEE initiated the program Super-Efficient Equipment Programme (SEEP). under this program, ceiling fan has been identified as the first appliance to adopted. SEEP for ceiling fans aims to leapfrog to an efficiency level which will be about 50% more efficient than market average by providing a time bound incentive to fan manufacturers to manufacture super-efficient (SE) fans and sell the same at a discounted price. The goal is to support the introduction and deployment of super-efficient 35W ceiling fans, as against the current average ceiling fan sold in Indian market with about 70W rating.

Energy Efficiency Services Limited (EESL) is an energy service company (ESCO) of the Government of India and is the world's largest public ESCO organized a program UJALA Ceiling Fan Distribution Scheme and National Energy Efficient Fan Programme. Under the program of EESL low price and 5 star rated Energy Efficient Fans are Being distributed.

1. Energy Efficient Fan Scheme of EESL:

   EESL launched the National Energy Efficient Fan Programme (NEEFP) to promote efficient use of energy by increasing the use of energy efficient fans at residential level.

   The cooling needs of most of the households in India are met by fans, as the use of ACs in households is still less than 10%. Considering the fact that about 30 million fans are sold every year, the potential to reduce electricity demand is quite high.

   Replacement of Regular Ceiling Fans with BEE 5 Star rated ceiling fans has the potential to save 47 Billion Units of energy annually. There are 35 crore inefficient fans in India, if all of these are replaced with BEE 5 star rated energy efficient fans, India will have annual energy savings of about 47 billion KWh, with corresponding reduction of over 12,250 MW of electricity demand.

2. Specifics of EESL Scheme:

Under National Energy Efficient Fan Programme, EESL provides BEE 5 Star rated ceiling fans which are 30% more energy efficient as compared to conventional fans. The energy efficient fans will be available to the consumers on an upfront payment of Rs. 1,150/- per fan.

EESL has distributed over 5 lakh energy efficient fans under this scheme which is expected to result in an energy savings of over 1.6 lakh kWh per day and a monetary savings of Rs 9.75 lakh per day to the consumers.

However, the higher price of the energy efficient 5 star rated fans is the primary reason for its low penetration along with the lack of awareness.

Payback period: With the usage of these energy efficient fans it is estimated that consumer's electricity bills will reduce by about Rs. 700-730 per year thus making the cost recovery in less than 2 years.

2.1 EESL scheme in Delhi (BRPL DISCOM):

   This scheme offers BEE 5 star rated Energy Efficient Fans, 50 W to consumers of BRPL at discounted price the fan will have a replacement warranty of two years for any defect.

   The price of Fan is fixed at Rs 1110/-per Fan. The saving expected per Fan is 25W per hour.

2.2 EESL Scheme in Andhra Pradesh:

   Distribution of Energy-Efficient, 50 Watts and 5-Star Rated Ceiling Fans.

   These fans are 30% more energy efficient as compared to conventional fans, which range from 75-80 Watts.

   At present, two energy efficient fans will be provided to each consumer at Rs 60 a month per fan on EMI basis. The EMI amount is added to the consumers' electricity bills for two years.

   This scheme will be available to the consumer on providing a copy of latest electricity bill along with a copy of residence proof at the designated distribution centre. The consumer can also purchase the fan by paying Rs. 1250/- upfront.

Consumer's electricity bill will reduce by about Rs 700-730 per year- which means that the cost of this fan can be recovered in less than 2 years.

PMBLDCM MOTOR BASED CEILING FAN

The PMBLDCM has been used in numerous kinds of industrial applications like transportation, robotics, automobiles and household. The PMBLDCM has changed the sector of appliances due to advantages of low maintenance cost, high efficiency, low electromagnetic interference, high flux density per unit volume, low noise, and availability of ranges for low to medium power rating motors with various applications drives[4,5]. The PMBLDCM has no brushes, so electronic commutation is implemented through driving algorithm and explained in this paper.

The PMBLDCM has been designed with moderate rated voltage three phase windings wound on the stator, which are excited by a voltage source inverter (VSI) and permanent magnets on the rotor inner surface to reduce losses in the motor and it enhances the power quality with a buck-boost power factor correction (PFC) converter to reduce energy consumption.

A buck-boost converter is utilized as a front-end converter to vary the DC link voltage for its speed control and converter has a smaller number of passive components and less losses. The switching pulses for the switch of front-end converter are designed in such a way, so as to ensure improvement in the power supply quality. Hence, the switching frequency of the switch should be as high as possible. In a PFC converter, a MOSFET is used as a switch with operating frequency of 25 kHz. The variation of speed of the motor, is controlled with change of DC link voltage and to feed the VSI for electronics commutation of the PMBLDCM.

PARAMETERS OF CONVERTER AND DRIVE

The parameters of converter feeding PMBLDCM based ceiling fan, are given here, which includes the calculation of components of the proposed converter.

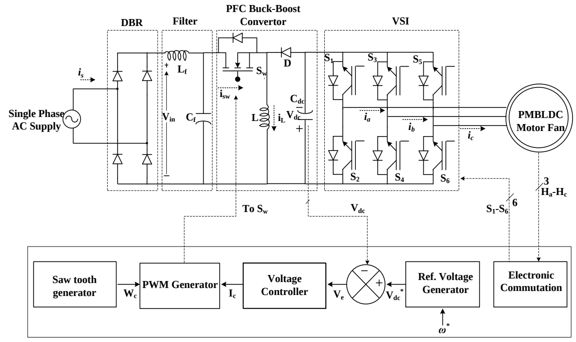

Figure 2: Circuit diagram of Proposed drive of the BLDC motor

The proposed buck-boost converter for ceiling fan motor drive, functions on the discontinuous current mode (DCM) as shown in **Figure 2**. In DCM of operation of buck boost converter, the current through input side inductor of the converter, becomes discontinuous in the switching period.

The designed power rating of PMBLDCM for a ceiling fan application is 35 W. It's designed maximum power output of the converter with safety factor of 25%, is a power of 43.75 W.

Therefore, based on the design calculation, following components are given in **Table 1** for the proposed converter.

COMPONENT	RATING
Inductor Lic	8.3 μH
Capacitor Cdc	600 μF
Input filter capacitance Cf max	50 nF
Input filter inductance Lf	3.3 mH

Table 1 Component of proposed Converter

CONTROL OF PROPOSED SYSTEM

The control of proposed PFC drive through a proportional integral speed controller and a pulse width modulation controller, to feed ceiling fan. There are mainly two techniques for PFC converter, current follower and voltage follower techniques.

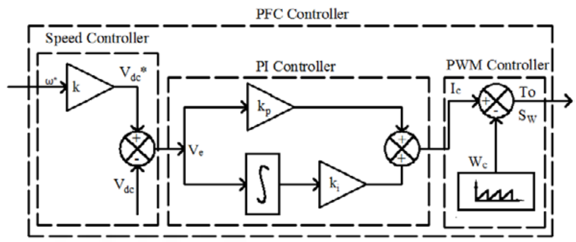

Figure 3: Control philosophy of drive segregated as speed controller, PI controller and PWM controller to fed PMBLDCM based Ceiling fan applications

Former one requires one current sensor and two voltage sensors. In this technique, rectifier output voltage is sensed and input inductor current is forced to follow the voltage waveform. The output voltage of this converter is regulated by PI controller. Therefore, this technique requires sensing of rectifier output voltage, voltage of DC link, and current of inductor.

In later technique, only one sensor is used and the converter is operated in DCM mode. Hence, stress is slightly high across the switch. The DCM mode has advantage of less sensors, which requires only DC link voltage sensor. The error signal is generated with a comparison of sensed voltage of DC link and voltage reference, which is fed to PI controller. The pulse width modulation of the electronic switch of proposed converter is realized through a comparison of output of PI controller and high frequency carrier wave. For the speed control of PMBLDCM, the reference speed is converted in terms of reference voltage. In steady state, neglecting small drop across motor winding resistance, back emf of the motor is equal to the terminal voltage, and back emf is function of speed. Therefore, it is expressed as,

$$V_{ref} = k\omega_{ref} \tag{1}$$

SPEED CONTROLLER

If ω_{ref} be reference speed at k^{th} instant, then back emf is as,

$$E_b(k) = K\varphi\omega_{ref}(k) \tag{2}$$

and the terminal voltage is as,

$$V_t = 2\left(I_a R_a + E_b + L\frac{di}{dt}\right) \tag{3}$$

Neglecting small voltage drop across the inductor and resistor, terminal voltage (V_t) is equal to twice of back emf (E_b) of PMBLDCM is as,

$$V_{ref}(k) = 2E_b(k) = 2K\varphi\omega_{ref}(k) \tag{4}$$

PROPORTIONAL INTEGRAL CONTROLLER

The voltage reference, V_{dc}^* is compared to sensed voltage of DC link V_{dc} and the error signal, so generated, is fed to a proportional integral controller. If $V_{dc}^*(k)$ be the reference voltage, and $V_{dc}(k)$ be the voltage of DC link at k^{th} instant then, the error signal is as,

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \tag{5}$$

The output of PI controller is a control signal (I_c) as,

$$I_c(k) = I_c(k-1) + K_p\left(V_e(k) - V_e(k-1)\right) + K_i V_e(k) \tag{6}$$

Where, K_p and K_i are proportional and integral constants of proportional integral controller.

PWM CONTROLLER

This control signal is relatively checked with fixed frequency carrier signal (W_c). A 25 kHz is chosen as carrier signal frequency. If $W_c(k)$ be the carrier signal at k^{th} instant then,

If $I_c(k) > W_c(t)$ then S=1 (7)

If $I_c(k) <= W_c(t)$ then S=0 (8)

Where, S represents ON or OFF position of switch. If S=1, then switch is ON and if S=0, the switch is considered OFF.

ELECTRONIC COMMUTATION OF VSI

The PMBLDCM based ceiling fan fed by a voltage source inverter is derived through an electronic commutation.

Various combinations of Hall-Effect signals, generate switching pulses for operation of switches of VSI with the rotor position as given in **Table 2**. The rotor position is used to generate three Hall-Effect signals. Each particular rotor position with an interval of 60◦ is produced a combination of Hall-Effect signals[6]. It states that change of switches conduction with change of rotor position and only two switches conduct at particular instant of time, representing that reduced conduction losses with 120◦ conduction mode of operation of an inverter.

Rotor Position	Hall Sensor			Switching Pulses					
	H1	H2	H3	S1	S2	S3	S4	S5	S6
0 - 60	1	0	1	1	0	0	1	0	0
60 - 120	0	0	1	1	0	0	0	0	1
120 - 180	0	1	1	0	0	1	0	0	1

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180 - 240	0	1	0	0	1	1	0	0	0
240 - 300	1	1	0	0	1	0	0	1	0
300 - 360	1	0	0	0	0	0	1	1	0

Table 2 Six Switching Pulses of VSI reference to rotor position

HARDWARE IMPLEMENTATION OF BLDC CEILING FAN

The performance of PMBLDCM based ceiling fan fed from a non-isolated buck boost converter, is validated on a developed prototype with DSP (Digital Signal Processor) of TI (Texas Instrument) to drive PMBLDCM through Allegro Microsystem make three Hall Effect position sensors as shown in **Figure 4**. The windings of the motor, are wound to increase the DC link voltage rating of the motor. **Figure 5** shows the stator windings of market available PMBLDCM based ceiling fan and windings of the proposed drive of the ceiling fan to operate at higher DC link voltage.

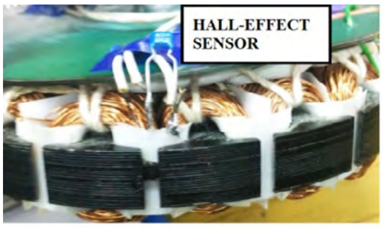

Figure 4: PMBLDCM through Allegro Microsystem make three Hall Effect position sensors

Figure 5: PMBLDCM based fan winding structures of (a) available ceiling fan, and (b) proposed drive

The MOSFET based PFC converter is gated through a gate drive IC IR2110. An isolation of DSP and gate driver of VSI and converter, is realized through an opto-coupler with IC 6N136. The performance of proposed drive is analyzed and compared with available fan in the market at various speeds of ceiling fan. The hardware of this system, is implemented by using Texas Instrument DSP.

PERFORMANCE OF EXISTING FAN

The performance of PMBLDCM fan available in the market i.e. supply voltage and current at variable speeds of fan, are captured through power analyzer as shown in **Figure 6**. The speed of the PMBLDCM based ceiling fan varies from 123 rpm to 332 rpm and power quality performance varies with the speed, which are tabulated in **Table 3**. An input voltage of ceiling fan standard single supply voltage, is 220V - 240 V 50 Hz and DC Link voltage rating of this fan is 24 V. The least power consumption of fan at minimum speed is 4.44 W and maximum power consumption at highest speed is 34.8 W whereas power factor changes from lower speed to higher speed from 0.8 to 0.376, which is major disadvantage of it, which attributes to electrical loading of winding increases to 400.3 mA.

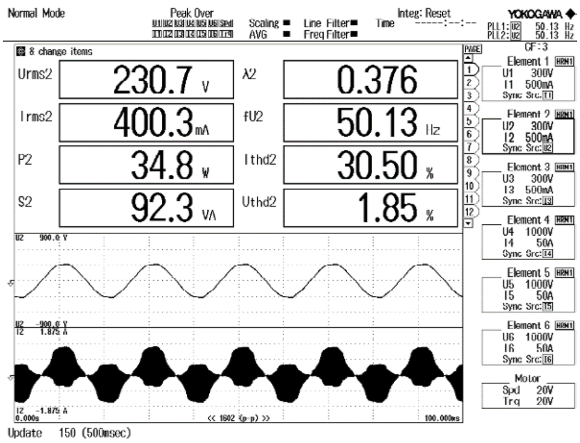

Figure 6: Performance of company manufacture PMBLDC Motor based Ceiling Fan at various speed 5

The THD of AC mains current of this fan, also increases up to 30.5% at rated (330 rpm) speed. The efficiency of the motor is evaluated approximately 69% where it is concluded that major losses its self in motor and converter of market product.

Speed	Speed (rpm)	Voltage (V)	Current (mA)	Power (W)	THD (%)	Power factor	DC link (V)
1	142	220.1	61.8	9.92	15.73	0.729	50.4
2	188	220.7	83.3	16.36	19.83	0.890	60
3	254	220.6	97.5	20.27	21.09	0.942	94
4	299	220.5	124.8	26.20	20.50	0.952	107.7
5	330	220.5	148.5	31.07	22.35	0.949	120

Table 3 Power quality performance of PMBLDC based ceiling fan available in market

PERFORMANCE OF PROPOSED DRIVE FAN

The performance of proposed drive and modified stator based PMBLDCM ceiling fan i.e. supply voltage and current, are shown in **Figure 7**. The proposed PMBLDCM based ceiling fan fed with single phase AC supply of 220 V – 240 V, 50 Hz and maxmium DC link voltgae upto 120 V. The speed of proposed PMBLDCM based ceiling fan varies from 142 to 330 rpm and the power quality performance with variable speed, are tabulated in **Table 4**. The least power consumption of fan at minimum speed is 9.92 W and maximum power consumption at highest speed is 31.07 W, whereas power factor changes from lower speed to higher speed from 0.729 to 0.949, which is major improvement in this case. The electrical loading of winding is reduced to 148.5 mA. The THD of AC mains current of this fan, is also improved up to 22.35% at rated (332 rpm) speed.

Hence, it is studied that the losses of the motor, are reduced with an increase of DC link voltage of the ceiling fan. The power consumption of the proposed PMBLDCM based ceiling fan, is 31 W, whereas at lower speed input power and THD of PMBLDCM of existing ceiling fan lower power consumption, but non-isolated PFC converter with modified stator winding of PMBLDCM ceiling fan power factor, is improved and power consumption at higher speed is reduced. The efficiency of motor is improved to 78% and losses are reduced with reduction of copper losses and converter losses with an increase in the DC link voltage and reduction current.

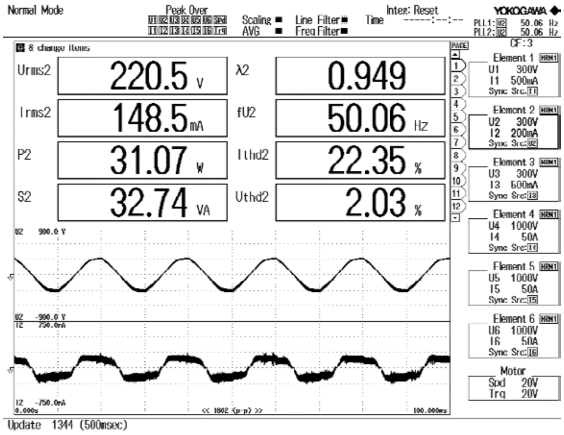

Figure 7: Performance of Proposed drive modified PMBLDC Motor based Ceiling Fan at speed 5

Speed	Speed (rpm)	Voltage (V)	Current (mA)	Power (W)	THD (%)	Power factor
1	123	230.8	24.08	4.444	15.36	0.800
2	184	230.8	35.14	7.50	10.52	0.924
3	255	230.7	102.6	15.44	29.53	0.652
4	299	230.8	171.8	23.16	16.69	0.584
5	332	230.7	400.3	34.8	30.50	0.376

Table 4 Power quality performance of proposed drive fed to PMBLDC motor based ceiling fan

FUTURE ROAD MAP TO ASSIST GOVERNMENT POLICIES

Government is encouraging the use of energy efficient appliances, which in-turn leads to use of more and more power electronics converters and inverters. Such topologies interfere with the power quality of the electric power supply and tends to lower the power factor & increase the total harmonics distortions. Consequently large number of substations have to be installed with power factor improvement devices (primarily switchablel or fixed capacitor banks) resulting in high cost implication.

Therefore, we suggest implementing the power quality standard codes & practice for the low rating appliances in India.

Even otheriwse, in many states of India, State Governments are providing subsidy on the electricity bills resulting in burden on the budget of the respective State. If Government looks into the prospects of encouraging the use of energy efficient appliances, this will reduce the burden of the monthly electricity bill on the consumer and also provide relief to the overburdened distribution network of the incumbent utility.

TECHNO ECONOMICAL ASPECTS

Based on the analysis of the market improved design induction motor based most efficient 5 star rated fan in the markets are available with power consumption of 45-50W, whereas BLDC based most efficient 5 star rated fan in the markets are available with power consumption of 30-35W. In respect of incremental cost of efficiency improvement is 700-1000 INR, which is equivalent to the saving cost of electricity bill of the two-years with assumption of 10 hr/per day within eight months of year running of the ceiling fan.

The proposed PMBLDC based ceiling fan costing will be similar in price range of the market available fan but proposed designed ceiling fan will be more efficient for long run time and low-speed performance. Detailed analysis of the each component of the ceiling fan is itself as a separate subject in itself.

LATEST GOVT. INITIATIVES

GOI Initiatives: The Government of India, and the World Bank signed a $220 million Loan Agreement and a $80 million Guarantee Agreement for the India Energy Efficiency Scale-Up Program. The Program is to be run through Energy Efficiency Services Limited (EESL), to help scale up the deployment of energy saving measures in the country.

The investments under the Program are expected to avoid total greenhouse gas emissions of 170 million tons of CO2. It will also contribute to avoiding an estimated 10 GW of additional generation capacity. This would be more than 50% of the National Mission for Enhanced Energy Efficiency target of 19.6 GW committed in India's Nationally Determined Contributions under the COP21 Paris Agreement.

CONCLUSION

The proposed PMBLDCM based ceiling fan has been fed through PFC converter i.e. non-isolated buck boost converter operated in DCM mode. It is analysed that with an increase of DC link voltage, the performance of the PMBLDCM based ceiling fan has improved. The power consumption at rated speed, is reduced by 12 % with an increase of the DC link voltage of DC – DC converter in DCM mode. The speed of the ceiling fan is controlled through variation of DC link voltage of VSI. The efficiency of proposed drive PMBLDCM is improved 9%. However, the modification of stator windings of PMBLDCM and change in converter system, have provided various scope of improvement of PMBLDCM based appliances as new technology in lower power consumption appliance. Such resolution may also apply to other appliances of the household to improve the power demand of residential sector.

New government policies encourage the manufacture and consumers design and innovate the new topologies of power electronics system to improve efficiency and power quality.

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ENERGY EFFICIENT CASCADE CONTROL OPERATION FOR VARIABLE SPEED PMSM BASED PUMPS

Arun Shankar V.K.[1], Paramasivam S[2]

[1]*Power Electronics and Drives - Research & Development*
Danfoss A/S Drives
Chennai, India.
arun.vishnu@danfoss.com

[2]*Power Electronics and Drives - Research & Development*
Danfoss A/S Drives
Chennai, India.
param@danfoss.com

ABSTRACT

In recent decades, global energy consumption increases rapidly with the development of modern industrial and commercial sectors. Hence effective utilization of energy is highly recommended to preserve the natural resources from depletion. Among the total electrical utilities installed in the globe, pumping system contributes to about 22 %. Most pumps are operated directly from AC supply and few are operated through VFDs. Parallel pumping is explored in few pump applications which are very limited. This research motivates the effective energy consumption method in permanent magnet synchronous motor (PMSM) based parallel centrifugal pumping system. The proposed control method involves ineffective staging and de-staging of parallel pumps connected in cascade mode without physical sensors. It works by estimating the flow rate of the centrifugal pumps and eventually controlling the speed of the parallel pumps, based on the flow demand. The efficiency is maintained at its maximum value throughout its entire operating flow rates in parallel pumping systems. Moreover, operating the pumps near its best efficiency region reduces risks of failure due to harmful pump operations. The performance validation of the suggested control methodology is implemented through real-time simulation and experimental setup verification. The experimental prototype consisting of three pumps in parallel is controlled individually using variable frequency converters. This new technology disrupts pumping energy needs by 42 % and can change India Energy Efficiency paradigm. In addition, the cost savings is calculated for the cascade pump setup when using proposed control method instead of conventional control algorithm.

Keywords—Centrifugal Pumps, Cascade pumping system, Energy Efficiency Enhancement, variable speed control, Permanent Magnet Synchronous Motor

INTRODUCTION

Energy plays a significant role in domestic and industrial utilities (Olszewski, 2016). Inefficient utilization of energy made depletion of natural resources and paves the way to global warming. Pumps are the major energy consuming utilities installed in almost all sectors (Arun Shankar *et al.*, 2016). Among them centrifugal pumps are most commonly used pumps due to their continuous output flow rate. They contribute to nearly 15 to 45% of the total energy consumption in the industrial drive applications depending on the operating conditions. Thus pumps exhibit huge energy savings opportunities by utilizing Variable Frequency Drives (VFDs). The need for enhancing energy efficiency and evolution in power electronics has led to the increase in use of Variable Frequency Drives (VFDs) for pumping system (Vodovozov *et al.*, 2016). The VFDs are preferred especially for process control applications, due to their wide range of flow control and minimal input power consumption (Bakman, Gevorkov and Vodovozov, 2015). The increase in energy demand from 1980 to 2030 is given by **Figure 1**(Arun Shankar *et al.*, 2016).

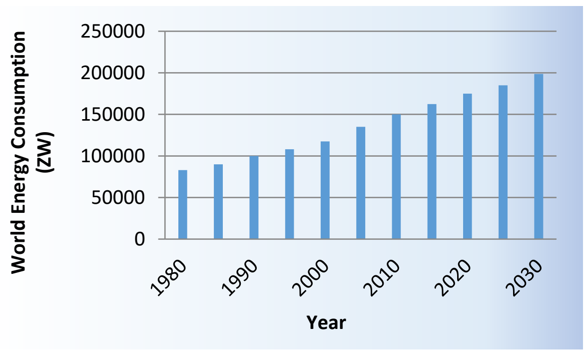

Figure 1: Energy demand statistics from 1980 to 2030

CENTRIFUGAL PUMPING SYSTEM

The flow rate of the pumping system is controlled over a wide range when the centrifugal pumps are operated in parallel, than as a single large unit. Also the total flow rate outcome of the entire system increases when the pumps are cascaded (i.e., pumps in parallel). In this research three centrifugal pumps connected in parallel with common suction and delivery is considered. Equations 1 and 2 represent the pumping system curve with static and dynamic head as shown below.

$$H_{sys} = H_{st} + H_{dyn} \tag{1}$$

$$H_{dyn} = k \cdot Q^2 \tag{2}$$

The working principle of cascade centrifugal pumps is illustrated in **figure 2(a) and (b)**. Pumps connected in cascade delivers the sum of an individual flow rate of each pump and common head exhibited by them. But when the pumps are operated with different rotational speed reference, the system characteristics of the entire pumping system varies, as all the pumps are connected to a single delivery. The total dynamic head (TDH) of a pumping system is given by equation 3.

$$H = \frac{\Delta p}{\rho g} = \frac{p_0 - p_i}{\rho g} \tag{3}$$

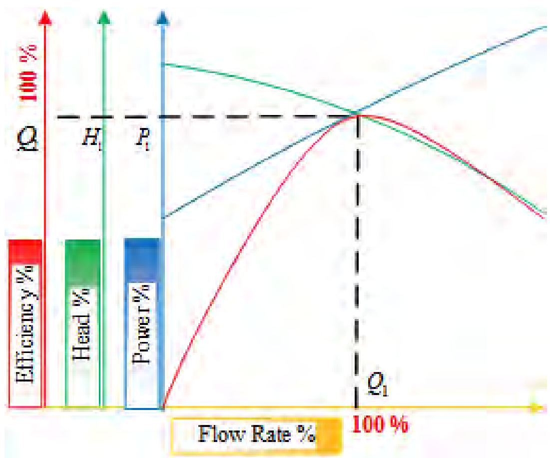

Figure 2a: Performance curve of centrifugal pumps

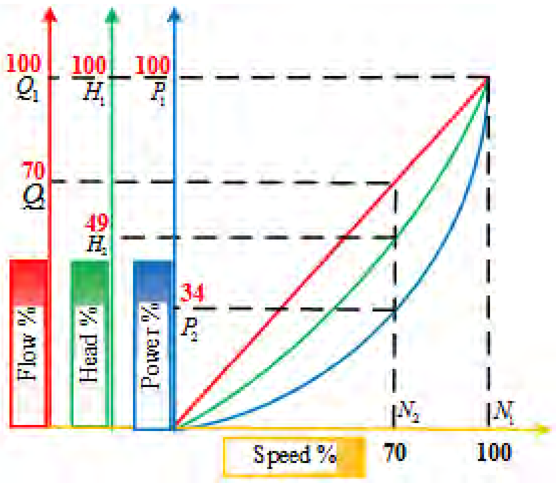

Figure 2b: Affinity Laws

Normally the operating point of the entire pumping system is identified as the intersection of the combined pump performance curve (i.e., Three pump curves together) and the system curve. Also the operating point of the individual pumps is estimated from the intersection of the y-intercept of the total pump curve with the individual pump performance curves. Normally the best practice in the selection of pumps with their operating point near maximum efficiency region is preferred for the pumping system. Moreover, operating pump away from the maximum efficiency region reduces lifetime and increases harmful effects like cavitation and shaft wearing(Ahonen *et al.*, 2014). The overall system efficiency of a parallel pumping system is given by equation 4.

$$\eta_p = \frac{Q \cdot \rho \cdot g \cdot H}{P_p} \tag{4}$$

The cascade centrifugal pump's output flow rate can be regulated through either, DOL, valves or variable speed control. The pumping applications prefer DOL method of flow control where the accuracy of output is not significantly high (Bakman and Vodovozov, 2012). In a similar way, throttling valves are mechanically controlled with lesser accuracy and they operate the pumps with higher losses and they also reduce pump efficiency. Thus, variable speed-based pumps are preferred over DOL and throttling valves for better efficiency and lower energy consumption. Some applications prefer variable speed control along with DOL to operate the pump near the best efficiency region. Traditionally single pumping unit is speed controlled using variable frequency drives for flow rate adjustments. Whereas operating two or three smaller pumping units instead of single larger unit enables various advantages (Arun Shankar *et al.*, 2017). When pumps are operated in parallel, the entire system efficiency can be optimized

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based on the individual operating points of the pumps. Also the production loss in a process industries would be significantly reduced when only one pump is recommended for maintenance. In a parallel pumping system normally, the primary pumps attain rated speed before staging the secondary pumps. The affinity laws (Flow rate, head, and power) for centrifugal pumping system is given by equation 5,6 and 7.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{5}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{6}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{7}$$

ENERGY EFFICIENT CASCADE PUMPING SYSTEM

The energy efficiency of a cascade pumping system with all pumps controlled through VFDs is higher than the conventional pumping system control. Besides energy efficiency, parallel pumps with speed control enhance the pump lifetime as it avoids the pumps to operate in the harmful region.

In this research, the experimental prototype consisting of three permanent magnet-based centrifugal pumps connected in parallel with each driven by a variable frequency drive is considered as shown in **figure 3.** When three identical centrifugal pumps are considered with a static head of 10 m and 3 cmph, the proposed control varies from the traditional control in proving reference to each pump. With the conventional control method, when the demand is 6 m^3/hr, both the pumps operate at maximum efficiency at rated rotational speed. Whereas in case of a process requirement with varying flow rate demand, both the pumps are speed controlled to achieve the necessary demand throughout the operating range as shown in **figure 4**.

The intersection of the system curve and the performance curve (QH Curve) provides the operating point of the entire pumping system. The comparison of both the pumps operated at different speeds, and at same speeds in order to achieve the required flow rate value is validated in this research.

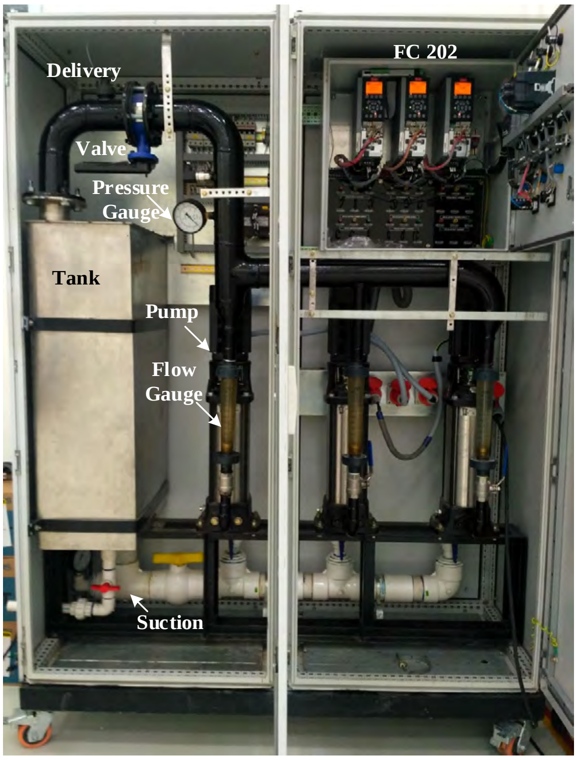

Figure 3: Parallel pumping experimental setup

Currently, conventional control serves as a better solution in achieving the user's set reference value (flow rate/ pressure). The sequential steps of master follower control are as follows,

1. When the user defies the reference value (ex. Flow rate/pressure) for the process closed loop, initially the first pump is gradually increased from zero to maximum speed to match the actual output of the pump (ex. Flow rate) with the set reference value.
2. If the reference value could not be achieved through a single pump although the pump reaching to its maximum speed, then the first pump waits for predefined time (i.e., Staging time – defined by user) and turns ON the second pump.
3. Simultaneously, the first pump drops to the minimum speed reference prescribed by the user and speed of the second pump increases gradually from zero to minimum speed reference.
4. Now speeds of both first and second pump are increased together from the minimum speed reference to the maximum speed reference by verifying the actual output flow rate with the reference value.

This process is repeated for the three pumps connected in parallel until the reference value is reached.

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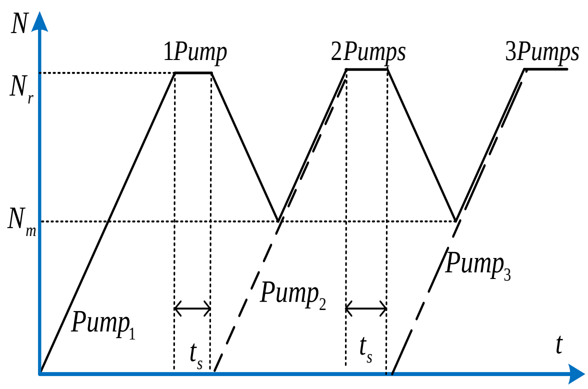

Figure 4:Conventional parallel pump Control

The sequential process of staging and de-staging of pumps using master follower operation is shown in **figure 4.** The power consumed at each stage (i.e., pump1; pump1&2; and pump 1,2 &3) for permanent magnet synchronous motor (PMSM) for 3 parallel pumps is shown in **figure 5.**

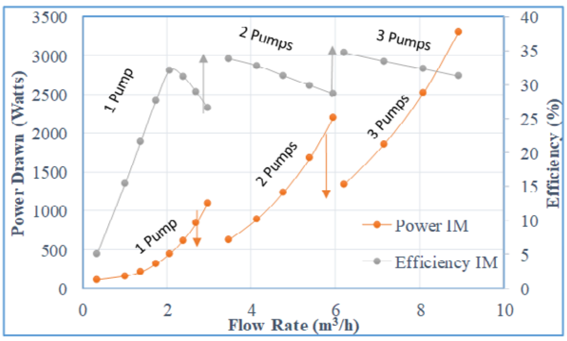

Figure 5: Power Consumption of PMSM based pumps with conventional parallel pump control

The proposed control is attempted to enhance the overall system efficiency of the parallel pump configuration in process control applications. It is accomplished by identifying power consumption at various operating points (flow rate) for all possible pump combinations and operating in the least power consumption region. The step by step working sequence of the proposed control is given by,

1. Initially, the total power consumed by the parallel pumping setup is observed for various operating points (i.e., flow rate from 0 to rated value) for possible combinations of pumps together (i.e, In a 3 pump configurations, 1 pump alone; 2 pumps; 3 pumps; and 4 pumps together).
2. From the values attained, the minimum power consumption locus is attained for the overall operating region (i.e, from 0 to maximum possible flow rate - Q_{max}) and it is given by the generalized equation,

$$N = \begin{cases} N_1 = a_1Q^2 + a_2Q + a_3; \quad N_2 = 0; \quad N_3 = 0, & Q_{min} \le Q < Q_{BPC1} \\ N_1 = N_2 = b_1Q^2 + b_2Q + b_3; \quad N_3 = 0, & Q_{BPC1} \le Q < Q_{BPC2} \\ N_1 = N_2 = N_3 = c_1Q^2 + c_2Q + c_3, & Q_{BPC2} \le Q \le Q_{max} \end{cases} \qquad (1)$$

3. For the experimental setup considered with 3 pumps (centrifugal pump -1.1 Kw), the equations are customized.
4. When the set reference value (ex. Flow rate) is defined by the user, initially the first pump is turned ON. For a given reference flow rate, the actual Flow rate produced by the first pump is verified by gradually increasing the pump speed from zero to speed at which least power consumption possible with both first and second pump together.
5. If the reference flow rate is not achieved through a single pump although the pump reaching to its least power consumption reference speed limit (N_{BPC1}), then the first pump waits for predefined time (i.e., Staging time – defined by user) and second pump is turned ON.
6. The speed of second pump is gradually increased from zero to the reference speed at which minimum power consumption occurred for the given flow rate and the first Pump is maintained at the same speed until pump 2 reaches its reference speed.
7. Now speeds of both pumps 1 and 2 are increased together from the minimal power consumption point (N_{BPC1}) to the next minimal power consumption point (N_{BPC2}) by verifying the actual output flow rate with the reference value.

This process is repeated for the 4 pumps connected in parallel until the reference value is reached by the actual value.

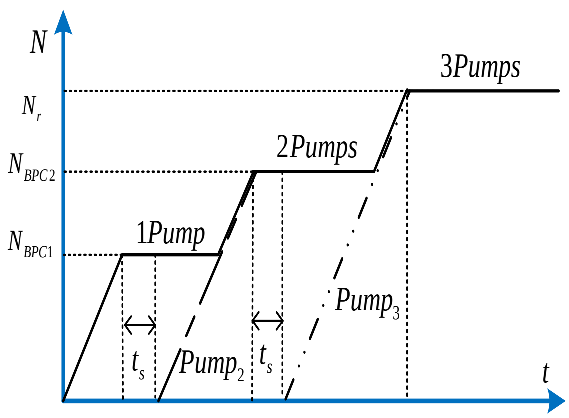

Figure 6: Proposed Control

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The staging and de-staging of pumps using the proposed control are shown in **figure 6.** The comparison of power consumption and efficiency for master follower and proposed control with permanent magnet synchronous motor (PMSM) is shown in **figure 7.**

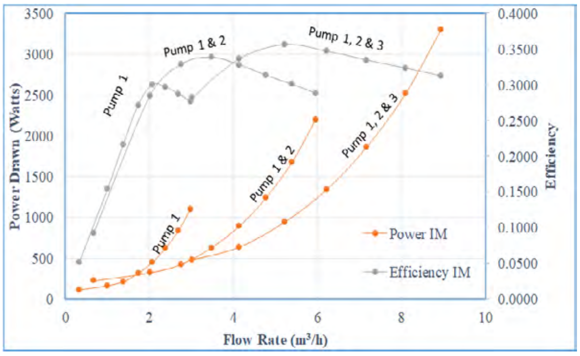

Figure 7: Power Consumption of PMSM based pumps with proposed pump control

DISCUSSION

The proposed control stages the second pump at the BEP of the first Pump, instead staging the second pump beyond the BEP that reduces the system efficiency. From the experimental results, for a given flow rate the BEP or the lowest power consumption occurs by operating two pumps together from 1.74 m^3/hr rather than single pump. Similarly, the process is repeated for staging the subsequent pumps (third Pump) at the BEP of both first pump & second pump in order to attain lesser power consumption. The area between the curves (Master Follower and the proposed algorithm) represents the power savings in that operating region as shown in **figure 8.**

LIFE CYCLE COST	CONVENTIONAL CONTROL	PROPOSED CONTROL
Initial Cost (3 x 1.1 kW)	124000	133000
Maintenance Cost(per year)	3000	3000
Operating time day (Hrs)	24	24
No. of operating days in a year	300	300
Set reference (cmph)	9	9
Power Drawn (W)	3309.7	1897
Energy Cost (Rs. / Kw-Hr)	6.5	6.5
Energy Consumed / year (Kw-Hr)	23829.84	13658.40
System Efficiency (%)	31.21	36.79
Energy savings (Kw-Hr)	-	10171.44
Earnings per year (Rs)	-	66114.36
Payback period (Years)	-	2.01
Payback rate	-	0.50
Rate of Return on an investment after 10 years	-	3.97

Table 1: Energy savings comparison

In **Table 1**, Conventional control, for a set point of 9 cmph, energy consumed per year is 23829.84 Kw-Hr (for 8 hours per day), whereas by proposed control with PMSM is 13658.40 Kw-Hr (for 24 hours per day). Therefore the energy savings per year is 10171.44 Kw-Hr. Therefore, with the energy price of Rs. 6.5 per Kw-Hr, the total earnings per year is Rs. 66114.36.

The total installation cost of pumping system (pumps, pipes and fittings) is Rs. 124000. Hence the pay-back period is given by 2.01 years.

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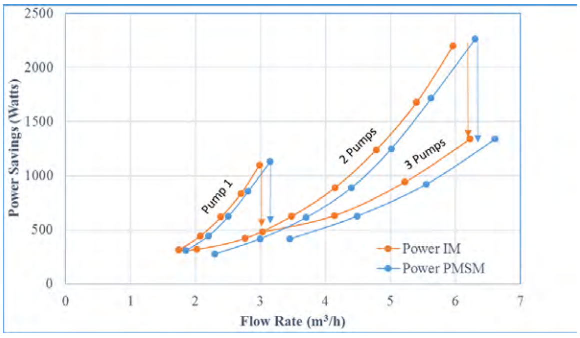

Figure 8: Power savings from conventional and proposed control.

CONCLUSION

The proposed control is validated and the results are obtained from the experimental prototype comprising three pumps connected in parallel each driven by VFDs. It can be applied for quadratic load applications of motor (i.e., Pumps, fans, compressors, and blowers) when they are connected in parallel. The conventional parallel pump control serves as the feasible solution for staging and de-staging of parallel pumps. However, it achieves the closed-loop process control with system efficiency/ power consumption not taken into consideration. In other words, it stages/De-stages the pump beyond the best efficiency point leading to higher power consumption that is undesirable. Thus the proposed control is introduced by considering the overall system efficiency of the cascade pumping system. In addition to enhancing energy efficiency of parallel pumps, the proposed control minimizes the harmful operations (i.e., cavitation, and water hammering).

NOMENCLATURE

Q = Flow rate [m3/hr]

P = power input [W]

η = Efficiency [%]

H = Pump Head [m]

N = Rotational Speed of pump [rpm]

k = Flow Constant.

VFD = Variable Frequency Drive

VSD = Variable Speed Drive

st = Static

dyn = Dynamic

o = Outlet pressure

i = Inlet Pressure

g = Gravitational constant

ρ = Density of the Liquid [Kg/m3]

Δp = Differential pressure

a,b,c = Pump coefficients.

1,2,3 =..Pump number.

min = minimum system speed

max = maximum system speed.

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IMPACT OF USE OF ENERGY ANALYTICAL PLATFORM ON BUSINESS AND OPERATIONAL EFFICIENCY OF FIRMS

Manoj Krishnan[1], Sajil Peethambaran[2],Vishnu R Nedungadi[3]

[1]*COO*
Greenturn Idea Factory
Cochin, India
manoj@greeniee.com

[2]*CTO*
Greenturn Idea Factory
Cochin, India
sajil@greeniee.com

[3]*Solutions Engineer*
Greenturn Idea Factory
Cochin, India
vishnu@greeniee.com

ABSTRACT

Energy charges across the globe are increasing as more countries are rapidly growing. Enterprises around the world are heavy consumers of energy with some spending millions on energy charges globally. However various research and studies point out that buildings waste 20-30% of energy that is consumed and this affects the performance of the enterprise. A key reason for this wastage is the fact that decision makers do not have visibility into energy usage at their premise. Hence, they do not understand if energy is being used optimally, or if there is any wastage and what the possible avenues to save energy are. In some cases, machine failure can also lead to lost productivity resulting in heavy financial losses for the enterprise. An energy analytics platform can help enterprises visualize their energy usage through data driven insights, identify areas of wastage and reduce it to save money, thus improving the bottom line of the business. This paper explores the history of energy monitoring systems, growth of energy analytics platforms, use of such a solution, what makes it different from similar traditional systems and the impact it has had on enterprise clients.

Keywords—Data Analytics, AI, IoT, Green Buildings, Predictive Maintenance

INTRODUCTION

Energy charges around the globe are increasing as more countries demand increasing share of resources to fuel their growth. In fact, in 2018, primary energy consumption grew at 2.9%, almost double the 10-year average of 1.5% and the fastest since 2010[1]. In the same time period carbon emissions grew by 2%, fastest rate for 7 years. The report paints a bleak picture about the future, if 2018 data becomes the norm, as both energy demand and carbon emissions grew at the fastest rate in years. This means that proactive measures are needed, if we are to manage both the growing energy demand and carbon emissions. According to US EPA, commercial and industrial sectors accounted for close to 62% of the total energy consumption in the US[2]. The studies also showed that 20 – 30% of the energy being used in a building / premise is wasted. Now compared to US, a developing economy like India has legacy electrical infrastructure which would result in an even larger energy wastage. Thus, for countries like India, where the usage of energy is expected to rise further as the countries continue to expand, the effects of energy wastage are higher. Addressing this issue would go a long way in ensuring sustainable development of these countries and the planet as a whole. Enterprise consumers are some of the highest consumers of electricity, with some of them spending millions on annual energy spends. Most enterprises view energy as a necessary evil, something that is needed 24X7, but something that is really hard to manage for optimal use. Most of them do not realize that managing their energy spends could be a single largest source of their competitive advantage. Energy management systems help enterprises understand their electricity usage, form a benchmark and track the benefits of implementing energy saving measures.

This paper explores the types of energy management systems in the market, the current state of such systems, current advancements and the benefits of such systems on enterprise clients.

[1]BP Statistical review of world energy - 2019
[2]US EPA website – Energy consumption by sector (2013)

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CURRENT TRENDS IN ENERGY MANAGEMENT

Monitoring and managing energy is very important for a firm to understand and benchmark their current electricity usage and be able to measure changes against this benchmark. The most common form of energy monitoring seen in most firms in developing economies like India, is manual monitoring – everyday usually at a set time, an employee, in most cases an electrician, goes around to all sub meters, notes down the meter reading in a book. Managing this data is usually a month end exercise where the data is tabulated and checked with the electricity bill from the energy utility, in the hope that there isn't much variation. The second most commonly found method is an energy audit which is done maybe once or a twice a year, when an energy auditor spends few days in the premise, studies the energy usage and gives his / her recommendation to save energy. However, the auditor can only spend a limited amount of time in a premise and the time that is spend needn't be representative of the typical energy usage at a premise, for the rest of the year. This means that energy bill usually increases few billing cycles after the audit is completed. Some of the newer premises might use smart meters. But these only make the data collection process easier, by avoiding need of manual intervention. They don't help in analyzing the data and presenting any useful insights to the user to effectively manage the energy spend at the premise.

This is where an Energy Management System (EMS) comes into play. An EMS is a tool, comprising of both hardware and software components, which helps to monitor, analyze and control energy consumption in a facility. The hardware solution could be energy meters or device that can extract data from exiting meters or custom-built hardware connected to the electrical infrastructure. The software helps in analyzing the data from the hardware and presenting insights to the user.

Importance of EMS rose with the rapid increase of fuel prices. During the period from 1973 to 1981, the primary concern of all the industries were to conserve their energy usage to mitigate the increase in fuel prices [4]. A lack of efficient techniques that enabled this meant that the effectiveness was meagre.

From 1981 to 1993, the focus shifted to managing energy, from saving it. Energy Management became popular during this period. Software to monitor and target energy (Building Energy Management Systems) was developed during this time period [4].

During the period of 1993-2000, the energy management industry saw a sharp decline. The two important factors of this decline were the reduction in real prices as a result of privatization of utilities and downsizing of general corporate [4]. As a result, attention shifted to energy purchasing from energy management. More effective purchasing strategies led to greater savings with lesser risks. It was during this time that environmental sustainability garnered attention. Though the environmental factors were incorporated into the Energy Management Techniques, it was not as effective as it was expected to be. Organizations primarily gave importance to Internal Rates of Return and often did not have the required technical personnel to identify, evaluate and implement the sustainable energy efficiency technologies.

Since the beginning of the new millennia, fuel prices increased at a rapid rate and as a result, many organizations were forced to make clear commitments to reduce consumption or face penalties for failure to do so. In the recent times, these systems have garnered a bigger audience since it enables organizations to gain competitive advantage and reduction in total energy costs without compromising on overall productivity. The recent amendment in government policies (in terms of rates, taxes, incentives, etc.) and increased focus on energy conservation and the limited availability of fossils have made the deployment of such systems even more crucial [2]. The Office of Industrial Technologies (OIT) and the Office of Energy Efficiency and Renewable Energy, with programs like the Best Practices (BP) program, the Industrial Assessment Center [IAC] program, and the Federal Energy Management program (FEMP), have been executed with the sole intention of better usage of energy and its conservation. The U.S government, with the help of the Department of Energy, has invested a huge amount of money and effort to help the industries and federal buildings reduce their power consumption via such programs [2]. The Indian government has also set up the Bureau of Energy Efficiency (BEE), to oversee use of energy efficient appliances and have set ambitious targets to make use of renewable energy sources, especially solar.

With the advent of tools for data analytics (Google PowerMeter, RETScreen Clean Energy Management

Software, EnergyCAP) [3], insights of never-seen-before magnitude are available to the end user very easily. Although, technology has advanced at a brisk pace, the end-use clients have not adopted the same quickly. Most of the potential buyers of energy management systems are at a stage where they are aware about the benefits of implementing such system but utilize traditional technology and applications for the purpose of energy management [1]. Financial barriers, limited expertise, and fragmented stakeholders are some of the key challenges for the energy management system market.

There exist a number of such solutions with a wide range of features. The most common mode of operation chosen by a majority of such solutions involves making changes to the wiring system (Invasive Techniques) to incorporate the solution (Ecostruxure from Schneider). It means that the entire circuitry of the involved facility has to be taken through the hub of such systems. These systems will be able to function only after that.

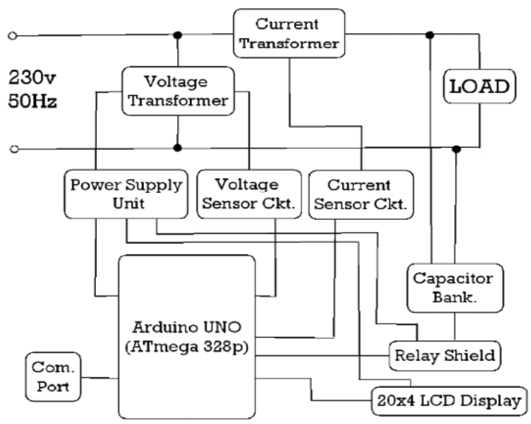

Figure 1: A Typical EMS based on Invasive Methodology

The advantage of this method is that, in addition to monitoring the entire facility, it also enables the user to control them from a remote location. (Eltrak from Elconn). Extensive control on the machinery installed is enabled for such solutions. The decisions are taken automatically by them with the help of complex algorithms in conjunction with PLCs and SCADA units. The downside is that, if the solution is being implemented in a facility that has been constructed fully, to make changes to the circuitry, the entire circuitry of the facility will have to be changed. This will add to the cost of installation of such systems and make the deployment even longer. For a long time, this issue has remained as the primary reason due to which many industries did not go for the deployment of Energy Management Systems in their premises.

The controlling feature of Energy Management Systems has always been a topic of debate. Though, it reduces the requirement of human involvement to keep the power levels at an optimum level, it remains a high-risk deployment from the point-of-view of industries, especially manufacturing plants. This is because it takes away from the engineer the inherent flexibility offered to him / her to manage the operations. The slightest increase of power consumption levels from the threshold value will inhibit the system from functioning. They will start again once the fault causing the power levels to rise have been properly addressed to. Hence most energy managers are skeptical on just depending on a completely automated system.

With the help of IoT and Data Analytics, in the present day, many companies have come up with solutions that do not require any change to the existing circuitry to provide accurate power consumption data. A generic block diagram of such a system is as shown in Figure 2. These solutions are either deployed as sub-metering solutions (Elmeasure) or plug-and-play models (Smart Plug by Suvana Solutions, Wemo Insight Smart Plug) at power point sockets.

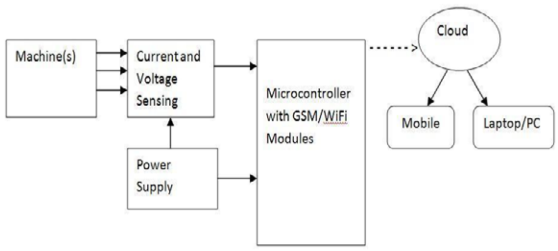

Figure 2: Generic Block Diagram of EMS based on IoT

They lack the controlling feature provided in the previous generations of Energy Management Systems, but they provide the engineers using them with necessary data to make that decision. The cost of such solutions typically varies from few hundred rupees to several lakhs, depending upon the extent of deployment and power capacity of solution used to cover the area. Such systems provide users with real-time data regarding their power consumption with minimal investment and maintenance requirements. Their deployment time is also considerably shorter when compared to the traditional EMS. The disadvantage of such systems till now has been that they have to be implemented as Sub-Metering Solutions. These systems also require sensors connected to each equipment / machinery in a premise. So even though the installation time might be faster than traditional EMS systems that need complete rewiring of the premise, it still involves considerable time and energy on behalf of the enterprise to get it operational. When deployed in such a manner, the total investment can go considerably high with an increase in the installation time as well.

A true IoT based Energy Monitoring System would avoid the need of having wired / sensor based connections to each equipment in a premise. This would mean that the deployment time would be considerably shortened, the solution would be easily retro-fitted even if the premise is new / old. Such systems are very few in the market, primarily because of the technological challenges involved in designing and developing such a system. The following section details such a solution in use today.

GREENIEE – A NON-INTRUSIVE ENERGY MONITORING SYSTEM

Greeniee is a Non-Intrusive Energy Monitoring System that addresses the aforementioned factors. A big drawback of existing systems, as explained in the earlier section, is the fact that all of them require some level of connection with each individual equipment or machinery in the premise – this can either be in the form of wired connections from each equipment / machinery or sensors connected to each individual equipment / machinery. This makes the whole installation process extremely time consuming and would involve shutting power and production meaning lengthy downtimes. Most enterprises do not go for such solutions unless they are installed before the building is occupied. Also, these systems are very expensive since it needs extensive rewiring and costly sensors.

Greeniee overcomes these challenges by taking a unique technological approach to energy measurement. The solution works on Non-Intrusive Load Monitoring (NILM) technique, which leverages custom built energy dis-aggregation algorithms. The hardware is installed at an electrical distribution panel level to break-away from the sub-metering model of deployment.

Various studies and research point that over 20% of the energy being consumed in a premise is wasted.

Figure 3: Picture of Greeniee hardware

A primary reason for this wastage is the fact that people do not have visibility into this energy usage. So, they are not sure if energy is being consumed in an optimal manner. Greeniee aims at shedding light into energy usage at a premise and also highlighting areas of energy wastage. The user will then be able to tackle the problems occurring at the premise much more efficiently.

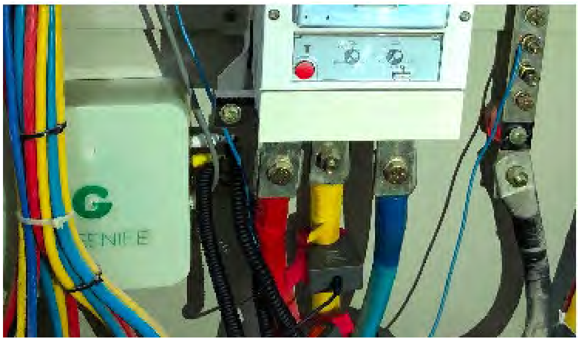

Figure 4: Picture of actual installation of Greeniee

Powered with a predictive algorithm, Greeniee maintains a continuous watch on the system 24x7x365 and offers real time visibility into energy usage, provides insights into equipment / machinery health, identifies wastage areas and offers recommendations to save energy. All this is done by analyzing the aggregate signal from the distribution panel, which is captured by the Greeniee hardware. The data is analyzed on the cloud enabling user to monitor and manage multiple premises, even on the go through a mobile app / web portal. A machine-level classification of real-time power consumption is made available to the user. Further information about overall parameters of the system, such as Three-Phase Imbalances and Power Factor drop is also made available to the user on a real-time basis. A hardware unit of Greeniee takes less than twenty minutes for deployment with virtually no change to the existing circuitry or down-time for the production plant.

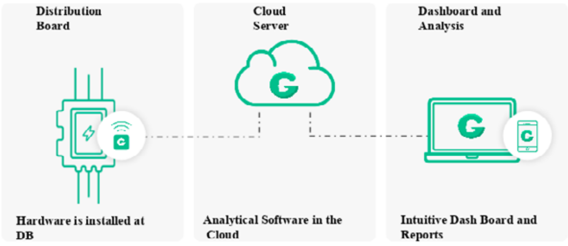

Figure 5: Architecture of Greeniee System

With the help of extensive reports provided, in the app and web portal, the user will be able to make necessary decisions to keep their power consumption levels at an optimum level. The data made available to the user include the wastage insights for their premise, historical hourly/daily/monthly electricity usage data for their premise, insights on phantom load, load imbalance etc. Greeniee also helps clients meet their sustainability goals by helping them understand their carbon footprint and giving them the ability to offset that against carbon credits. Clients also receive a detailed report of the findings and recommendations on saving energy, at the end of their billing cycle. This report provides actionable insights that the client can undertake to save energy at their premise.

Figure 6: The Greeniee Web Dashboard

Clients usually recover their cost within 1 year and over a 5-year period they save over 6X of the cost of the solution.

CASE STUDIES

This section highlights case studies of how clients have benefitted by using Greeniee

1. Load balancing - The solution was installed at a client who was operating and managing a co-working space. The client was facing issues with frequent ELCB tripping at their premise. Greeniee found out that one of the phases was heavily loaded with all heavy loads like AC chillers connected to that phase. This was causing the frequent tripping of ELCB. The heat losses associated with the heavy loads on this phase was also substantial. The client achieved a saving of 6% on their monthly electricity usage by balancing the load at the premise.

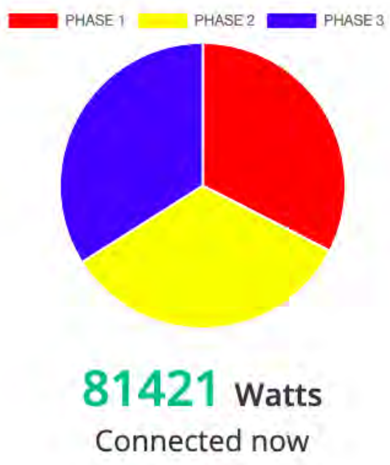

Figure 7: Comparison of load on each phase

2. Power Factor – Most electricity utilities impose heavy fines if power factor falls below 0.9. Most firms design their capacitor banks to keep their power factors above 0.9, but the actual figures on the ground varies and firms do not usually understand this, until they receive the fine from the utility. The solution helps clients understand the power factor at their premise in real time and alerts them if it falls below 0.9, so that they can take corrective measures. For a client, a hospital, the client found out after installing Greeniee that their power factor was consistently below 0.9 and that the capacitor bank designed wasn't accurate for their load profile. This helped them design the capacitor bank for their correct load profile.

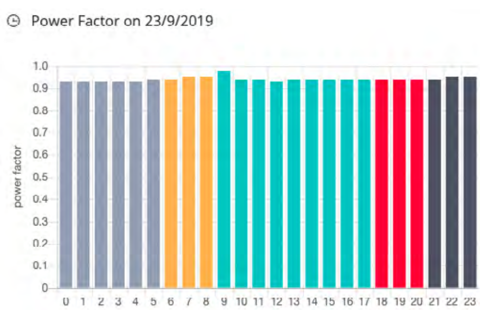

Figure 8: Hourly trend of power factor

3. Preventive maintenance – For clients especially in industrial setting, ensuring that the machinery or equipment operate in an optimal manner,

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without impacting productivity is critical. A client running a textile dyeing unit, after installing and running Greeniee, found out that a motor in a machine was consuming more power than it should have been consuming. On seeing the alert, the client

Soft Flow 3T	83.41	₹ 543.46	11hr 46min
Soft Flow 4P	73.01	₹ 476.70	10hr 40min
Soft Flow 2T	30.52	₹ 201.80	10hr 32min
Effluent Pump	16.47	₹ 105.07	02hr 05min
Water Pressure Feed	13.70	₹ 89.20	11hr 02min
Soft Flow 1P/2P	9.90	₹ 64.55	11hr 24min
Soft Flow 3P	9.77	₹ 63.88	06hr 27min
Brine pump	9.30	₹ 60.56	01hr 23min
SPI Oven	5.98	₹ 38.44	04hr 20min
Starlet Dye Machine	5.82	₹ 35.09	01hr 28min
Dispensor	2.23	₹ 14.24	04hr 53min

Figure 9: Itemized report of consumption

investigated the matter further and found out that the motor was about to fail. They were thus able to schedule the maintenance before the machine stopped working. The productivity loss that was avoided by the client – it would have taken at least 2 weeks to receive a replacement part as the machine was imported from Italy, was worth a few million rupees.

4. Phantom load – Phantom load is the always on load at a premise. Even if all equipment or machinery are switched off, there will be a certain power consumption at the premise, and this constitutes the phantom load. Many enterprises don't realize that phantom load could be the single biggest contributor towards energy wastage and high energy bills. One of the firms, a large amusement park, where the solution was installed realized that, almost 50% of their connected load was due to phantom load and for this business, this should never have been the case. When the issue was inspected it was found that there was a continuous current leak in one of the ETP motors.

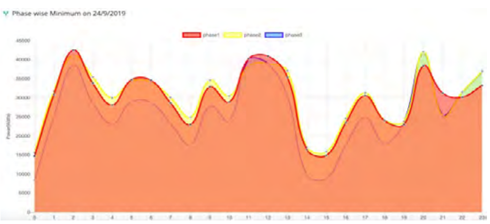

Figure 10: Phase wise load distribution

5. Carbon Footprint – Clients can understand their carbon footprint, to help them better manage their sustainability goals by offsetting their carbon footprint. This helps them contribute to the sustainable development of the planet.

Figure 11: Carbon footprint

CONCLUSION

The current scenario in the Industrial Domain requires us to take efficient steps to ensure proper usage of energy and cut down wastage whenever and wherever possible. With the help of IoT and Data Analytics, technology today provides various means to address this issue.

Intrusive Load Monitoring based solutions, though it addresses the concerns, are very costly and time consuming to be deployed. In terms of ease-of-use, installation and valuable insights of the system being monitored, a Non-intrusive solution like Greeniee helps the customer take the necessary steps to improve their energy usage with least effort for the cost. Greeniee helps clients reduce electricity consumption by 10-15%. This provides clients with significant improvements to their business bottom-line. A quick rate of return of investment makes such solutions one of the more powerful tools to tackle the problem of energy management with relative ease. Such systems will help immensely in the fight against climate change and provides significant monetary benefits to clients, incentivizing them to use it.

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ENERGY EFFICIENCY IN MSME SEGMENT – OPPORTUNITY, CHALLENGES AND POSSIBLE SOLUTIONS

Rohit Chashta[1], Aalok A. Deshmukh[2]

[1]*Energy Efficiency*
Schneider Electric
Gurgaon, India
rohit.chashta@se.com

[2]*Energy Efficiency*
Schneider Electric
Gurgaon, India
aalok.deshmukh@se.com

ABSTRACT

The Micro, Small and Medium Enterprises (MSMEs) segment of India contributes to 28% of India's GDP and accounts for nearly 40% of the exports from the country.

This paper discusses the significant energy efficiency opportunities in different MSME sectors (foundry, forging, die-casting, etc.) where the energy cost ranges from 30 – 50% of the total production cost. Though there have been several programs and initiatives from government and non-government organizations and financial institutions, there are still a lot of challenges in implementing energy efficiency projects at MSMEs. Some of these challenges are:

1) Reluctance by MSMEs to switch to new technologies,
2) Energy consultancy and audits provided to MSMEs are of very basic nature,
3) Financing for energy efficiency projects has not scaled up.

Some possible solutions to overcome these challenges can be:

1) The identification and creation of agencies with budgetary support to implement pilot projects and demonstrate new and advanced technologies,
2) Under any MSME program, the energy consultants and auditors must be made aware of the latest technologies, along with their advantages,
3) To improve energy efficiency financing, a portfolio of projects can be financed as opposed to financing individual ones. A loan portfolio can also be created by pooling various project ticket sizes through an aggregator.

The paper concludes with a discussion of the opportunities, challenges, and possible solutions along with a discussion on specific case studies of two MSME clusters.

Keywords— Energy Efficiency, MSME, Industries, Energy Efficiency Financing, Advanced Technologies

INTRODUCTION

The Micro, Small and Medium Enterprises (MSME) sector has emerged as a highly vibrant and dynamic sector of the Indian economy over the last five decades. It contributes significantly to the economic and social development of the country by fostering entrepreneurship and generating largest employment opportunities at comparatively lower capital cost, next only to agriculture. MSMEs are complementary to large industries as ancillary units and this sector contributes significantly in the inclusive industrial development of the country.

The MSME sector is a heterogeneous sector in terms of the products manufactured, sizes, manufacturing processes, output and technology used in manufacturing. MSMEs engaged in manufacturing, account for about 33% of India's manufacturing output and around 28% contribution in the GDP as whole (MoMSME, 2018-19). With more than 117 million jobs (20% of the total indian workforce) provided by 63 million working MSMEs across the country, this sector is often regarded as one of the most diverse and dynamic part of the industries.

The Ministry of Micro, Small, and Medium Enterprises (MoMSME), which is the apex body for drafting policies under the Development Commissioner (DC-MSME) wing, has implemented or launched 26 schemes which target MSMEs. Three of these schemes specifically target technological upgradation and energy efficiency in MSMEs: Credit Linked Capital Subsidy Scheme (CLCSS), Credit Guarantee Trust Fund for Micro and Small Enterprises (CGTMSE), and Scheme for Technology and Quality Upgradation Support to Micro, Small and Medium Enterprises (TEQUP). A budgetary analysis of the TEQUP scheme, which primarily aims to increase manufacturers' awareness of the benefits of energy efficiency and to facilitate financing of energy-efficient technologies (EETs) through capital subsidies, shows a high percentage of unutilised funds (71 per cent), and the scheme itself constitutes less than one per cent of the overall budget of the ministry (Tirtha, et al., 2018).

OPPORTUNITIES FOR ENERGY EFFICIENCY IN THE MSME SEGMENT

As mentioned in the introductory section, there are around 63 million working MSMEs, distributed across more than 6,000 clusters in India (MoMSME, 2018-19). MSMEs across the country employ highly varied manufacturing processes to produce similar products. Most enterprises in India are small-scale operations with a small capital base and poor access to timely and adequate finance; therefore, they lack the resources to implement the technology solutions available in the market. Instead, they opt for low-cost sub-standard solutions, leading to further inefficiencies in production processes. Enterprises operating in energy-intensive industries like brick manufacturing, foundries, glass, ceramics, and textile dyeing incur disproportionately high energy costs. For example, a small-scale ceramics manufacturing firm can easily spend 35-40 per cent of its total production expenditure on energy.

SECTOR	ENERGY COST AS A SHARE OF TOTAL MANUFACTURING COST	IN MONETARY TERMS (ANNUAL) (MILLION INR)
Forging	50 %	33
Foundry	50 %	41
Die casting	35 %	11
Ceramics	35-40 %	12 to 14

Table 1: Energy cost across key energy-intensive sectors (SIDBI, 2016)

MSMEs in India are also vulnerable to price fluctuations as they pay more per unit of energy compared to larger enterprises (TERI, 2015), and they typically use outdated or inefficient technologies. Such inefficiencies lead to higher energy costs and lower profit margins, especially for energy-intensive operations. Energy-efficient technologies potentially offer lower energy costs, lower raw material costs, and higher productivity, thus improving the production quality.

MSMEs alone could potentially take up sixteen per cent of India's total energy-efficiency market (Pacharne, et al., 2014). The energy savings that could result from adopting energy efficiency technologies across various MSME sectors is shown in Table 2.

SECTOR	ENERGY SAVINGS POTENTIAL	IN MONETARY TERMS (ANNUAL) (MILLION INR)
Forging	20 %	6.6
Foundry	10-30 %	4.1 to 12
Die casting	10-20 %	1.1 to 2.2
Ceramics	15-30 %	2.0 to 4.0

Table 2: Energy savings potential across key industrial sectors in the MSME sector (SIDBI, 2016)

As evident from Table 2, on an average, all the MSME sectors offer 10 – 30% energy savings potential, which translates to INR 1 million to INR 12 million, in terms of energy costs.

Note: The monetary values in table 1 and table 2 are approximate figures, calculated through interpolation and extrapolation from Sameeeksha and TERI reports for MSME cluster profiles.

CHALLENGES AND POSSIBLE SOLUTIONS FOR IMPLEMENTING ENERGY EFFICIENCY PROJECTS IN MSME SEGMENT

Below are the key challenges and possible solutions for scaling up the implementation of energy efficiency projects in MSMEs in India.

Lack Of Energy Data And Benchmarking

The absence of energy consumption and benchmarking data for the MSME sector has been repeatedly highlighted in the past; the lack of a comprehensive database leaves policy planners and researchers no option but to resort to estimations of energy consumption. This highly approximate information does not truly represent trends in actual energy consumption in the MSME sector. Afterall, we can't manage what we don't measure.

Possible solution(s): To design and optimise schemes effectively, it is imperative to collect primary data on the energy consumption and productivity of MSMEs. Data on energy consumption is readily available with the enterprises. As per a survey done by CEEW, covering 429 enterprises from 11 MSME clusters across 8 states, it was highlighted that 88 per cent of respondents record their energy consumption data in some form. The Ministry of MSME (MoMSME) started the MSME databank with the aim of collecting information on the physical and financial performance of the units registered with it. As a first step, this platform could be extended to include voluntary reporting on energy consumption by MSMEs. This would provide a more accurate estimate of the actual energy consumption of MSME units in various energy-intensive and non-energy-intensive sectors. Voluntary reporting could be incentivised at first, in order to get MSMEs to share their energy consumption data, while providing details (quantity and price) on fuels consumed from various sources. Through these benchmarking practices, MoMSME can also help the MSMEs in becoming energy efficient, by setting up of voluntary energy targets for the relatively high energy-intensive sectors, and then rewarding the ones who are able to achieve their targets. In the second stage, a scheme similar to the Perform Achieve Trade (PAT) scheme run by the Bureau of Energy Efficiency (BEE) to reduce specific energy consumption in select high energy-consuming industries across India. The learnings from the PAT scheme could also be extended to the whole of the MSME sector. To begin with, this could be rolled out in a few energy-intensive sectors like forging, foundry, steel re-rolling, textiles, etc.

Reluctance In Switching To New Technologies

MSMEs by their very nature are spread out across the country and dispersed; not located in any one particular geography, leveraging local skills, materials, and markets to create a consumer base for their products or intermediates. While energy efficiency pilots and technology demonstrations have been conducted in the past, they have received active support from only a handful of institutions, limiting their reach and impact. Thus, lack of awareness about new technologies and concepts like life-cycle cost and techno-commercial analysis, become one of the major hurdles for MSMEs to switch to a new or an advanced energy efficiency technology.

Possible solution(s): In the last one year, the authors' organization has been a part of a series of "CleanTech" workshop events (more than 20 events, across 15 pan-India locations), as technology providers for industrial automation and IoT (Internet of Things) solutions. These events were organized by BEE, SIDBI, World Bank, and PwC, under the Global Environment Facility (GEF) – World Bank Project for 'Financing Energy Efficiency at MSMEs'. These were essentially awareness and capacity building workshops on resource efficiency measures for various MSME clusters.

With this experience, we have learned that enterprises that access information related to a program or a technology solution from their peers are more likely to invest in energy efficiency measures. Peers play an important role in the decision-making of an enterprise owner with regards to investing in energy efficiency. Therefore, it's extremely important to organize more such events, and as a priority action point, agencies should be designated to implement and demonstrate pilot projects of new technologies that can help in improving the energy productivity of the MSMEs.

The above-mentioned CleanTech events were a great example of an effort to increase the awareness among the MSMEs by showcasing the latest technology with case studies and felicitating the MSMEs that have implemented energy efficiency measures. Awareness sessions included information on standards like ISO 50001 and how they can help a facility in establishing an Energy Management System. The events included presentations and demonstration (at exhibit spaces), by technology providers, of new technologies, along with information on use cases in the particular MSME sector.

As mentioned above as a priority action item, these efforts can be further amplified by setting up an institutional arrangement consisting of various technology developers, (technology) implementing agencies, and financial institutions; aimed at carrying out pilots and technology demonstrations. These projects must be accompanied by a business case; with a commercial component and a demonstrated ability to generate revenue after completion. These pilot projects and demonstrations will provide assurance to financial institutions regarding the performance of energy efficiency technologies and other energy efficiency interventions by MSMEs, and will in turn lead to technical capacity building within the financial institutions, enabling them to better appraise such interventions. These institutions can also aggregate data to develop performance benchmarks for various EE technologies used across industrial sectors.

Energy Consultants And Auditors Are Not Aware About New Technologies

Through our experience with the CleanTech events, we noticed that energy consultancy and audits provided to the MSMEs are of very basic nature, which denies the enterprises the opportunity to get updated with the new and latest technologies. Furthermore, even if these enterprises do get to know about the new technologies, they are not aware about the commercial aspects like payback and ROI, which again hinders MSMEs from switching to new technology.

Possible solution(s): Energy auditors and consultants, especially the ones providing consultancy and audits for the MSME segment, need to be updated with the latest available technology and their techno-commercial aspects as well. One such initiative that was taken this year, which Schneider Electric was also a part of, was the Manufacturing Excellence & Innovation Mission, by CII, to visit, experience, and learn about Industry 4.0 and Innovation. One such visit was to one of Schneider Electric's smart factory and its R&D center in Bangalore, where the CII team, along with representatives of several manufacturers saw firsthand a live showcase of a smart factory and a functional Industry 4.0 setup powered by the Industrial Internet of Things (IIOT). Since CII is one of the front-runners in performing energy audits or providing consultancy to MSMEs, these kinds of initiatives, of providing up-to-date information to industry associations, their member ogranizations and auditors about the state-of-the-shelf technologies in the industrial setting, can also help MSMEs to know more about the most recent energy efficiency technology developments.

Lack Of Financing

Despite several efforts, the percentage of MSMEs taking advantage of institutional finance is very small. MSMEs still prefer to undertake renovation and modernizations either using their own funds or borrowing from informal financing channels. As per the statistics compiled in the most recent (2017) census of MSME sector for registered units, only about 16% of MSMEs availed finance from formal sources like banking, non-banking, and government institutions. The vast majority of about 84% units had either not borrowed funds or had depended on internal sources.

The major reason for the miniscule credit flow to this sector is that the MSMEs are considered to be a high risk sector by the banks. This is due to several factors such as poor book-keeping practices, weak balance sheets, poor credit history and smaller sizes of MSME loans. Bankers adopt a collateral-based lending approach for MSMEs rather than cash-flow analysis approach which is used for loans to large-scale industries.

Possible solution(s): Various studies have highlighted that partial risk mitigation mechanisms such as the Partial Risk Guarantee Fund for Energy Efficiency (PRGFEE) by BEE and the Partial Risk Sharing Facility (PRSF) by SIDBI can be appropriate tools to address the credit risk associated with an investment. These mechanisms are aimed at lowering the risk for the banker by guaranteeing partial repayment of the loan in case of default. In order for a project to be eligible for a guarantee, it must have demonstrable energy savings, viable technology, and a method to measure and verify (M&V) the energy savings from the project. However, the absence of data on performance standards and benchmarking parameters for various energy efficiency technologies result in low confidence at an industrial scale in these seemingly unproven technologies, thereby increasing the perceived risks for the proposed loans. Energy efficiency investments must be made attractive to financiers by demonstrating and validating, at an industrial scale, the performance, installation time and costs, operation and maintenance costs, and reliability and operating lifetimes of various technology interventions.

Through our engagement with MSMEs during the CleanTech workshops and other similar events, one of the findings has been that high transaction costs can be reduced by financing a portfolio of projects as opposed to financing individual ones. The credit requirements of MSMEs are usually defined by smaller ticket sizes. A loan portfolio could be created by pooling all such ticket sizes through an aggregator, in this case a cluster association or a designated institution appointed by the state or central ministry. This could be along the lines of the work that Energy Efficiency Services Limited (EESL) has done with its national level energy efficiency or demand-side management projects, where they have aggregated thousands of small-ticket projects having similar technology intervention, and then financed or arranged for financing for the whole collective project as one.

It must be noted here that the solutions suggested in this paper are based on the experience of the authors' work in the MSME segment. As of now, there seems to be a dearth of replicable business models and implementation success stories, in the MSME segment, that can be showcased here.

CASE STUDIES

As part of the CleanTech workshops, we presented our automation & IoT technology at various MSME cluster locations. Below are two case studies from Faridabad and Ankleshwar, based on our experiences and interactions with MSMEs in those two clusters.

Faridabad Cluster

One of the largest and fastest growing MSME clusters in India is located in Faridabad, Haryana. Faridabad is located just 25 km away from Delhi, and is well connected to the rest of the country by rail and road. The number of MSMEs in the cluster registered a sharp increase from 2006–07 onwards, following the signing of an MOU between the Japanese and Indian governments that year for the Delhi–Mumbai Industrial Corridor (DMIC) Project which passes through Faridabad. There are an estimated 12,015 MSME units in the cluster, of which 38% are micro units, 59% are small-scale, and 3% are medium-scale units. About 60% of all the MSMEs in the Faridabad cluster fall under three broad industry sectors—automobile parts (35%), sheet metal components (14%) and fabrication (11%) (TERI & DESL, 2014) The other major industry sectors include castings, chemicals & paints, electroplating, forging, heat treatment, industrial fasteners, plastic products, railway equipment, rubber products, and textiles.

Energy saving potential: Energy costs account for a significant portion of manufacturing costs, varying from just over 2% in fabrication units to over 44% in foundry units. While a number of units have taken measures to upgrade their technologies, there exists a significant potential to improve the energy efficiency of the existing systems and processes. Based on our (Schneider Electric's) discussions with the MSMEs in the Faridabad region, some of those measures are – automating the processes with PLC-based applications like a temperature-based control system for furnaces; duty-cycle mapped variable frequency drives for pumps and compressors; installation of an energy management system to get operational visibility and effectiveness; power quality solutions for improving power factor and reducing harmonics; and IoT-based smart switchgear to enable predictive maintenance capabilities.

Challenges:

1) Lack of awareness about techno-commercial aspects of energy efficiency measures, with no specific guidelines on purchase of energy efficient equipment.
2) Although energy efficiency workshops have been organized for MSME owners, but for a mixed cluster like Faridabad, sector-specific workshops are needed.
3) Success stories for implementation of energy efficiency measures are not available or circulated within the cluster.

Possible Solutions:

1) Role of nodal agencies like cluster associations should be enhanced in order to provide more awareness about various aspects of energy efficiency measures to the MSME units.
2) Sharing of best practices among the MSMEs, and for mixed clusters like Faridabad, it should be sector specific suucess stories or best practices.
3) During future energy efficiency programs for conducing energy audits in the MSME units, it would be better to rope in process experts along with energy auditors, so that both process and utility related energy efficiency levers are identified.

Ankleshwar Cluster

Ankleshwar is an industrial town located in the Bharuch district of Gujarat. The Ankleshwar MSME cluster has more than 700 MSME units manufacturing various types of chemicals, like dyes, pigments, insecticides, specialty chemicals, petrochemicals, pharmaceuticals, and paints. Out of the 700 units, 38% are micro units, 59% are small-scale, and 3% are medium-scale units. The MSME units in Ankleshwar fall under two broad industry sectors – dyes & pigments (67%) and pharmaceuticals (27%) (TERI, 2014).

Energy saving potential: Energy costs account for a considerable portion of manufacturing costs, varying from 5% in organic chemical units to over 15% in dyes and chemical units. Based on our (Schneider Electric's) discussions with the MSMEs in the Ankleshwar region, some of the energy efficiency measures that we found common in most of the units are – automating the processes with PLC-based applications like a temperature-based control system for steam generating units and boilers to avoid wastage of thermal energy, duty-cycle mapped variable frequency drives for thermic fluid heaters (including temperature-based controls as well), pumps, compressors, and chillers; installation of an energy management system for operational visibility and effective load management; power quality solutions for improving power factor (avoiding excess demand penalties) and reducing harmonics; and IoT - enabled smart switchgear to enable predictive maintenance capabilities, especially for motor faliures, and burning of motor windings.

Challenges:

1) An active central body or cluster association is needed.
2) As is the case with the Faridabad cluster, in the Ankleshwar too, a lack of awareness about different aspects of energy efficiency measures is one of the biggest challenges.
3) Although energy audits are conducted, the recommendations given are very generic and not sector specific.

Possible Solutions:

1) A central agency at the cluster level can be formulated for maintaining better coordination and tracking cluster-level progress, besides bringing awareness to the MSME units for the implementaton of energy efficiency measures.
2) Process energy constitutes a major portion of energy use in the Ankleshwar sector units. Therefore, process-specific energy audits needed, along with specific recommendations and financial analysis of the energy efficiency projects.

CONCLUSION

Significant untapped energy efficiency opportunities exist in different MSME clusters and sectors. There are several challenges that hinder adoption of energy efficiency measures. However, there are possible solutions and approaches that we can and must explore, to overcome these challenges; so as to effectively drive the widespread implementation of energy efficiency projects in the MSME units.

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FOULING CONTROL TECHNOLOGY APPLICATION IN CDU/VDU-NRL

Ms Geetali Kalita
Technical Services department
Numaligarh Refinery Limited
Golaghat, Assam, India
Geetali.kalita@nrl.co.in

ABSTRACT

Numaligarh Refinery Limited (NRL) is 3.0 MMTPA refinery processing predominantly Assam crude oil from OIL and ONGC. Crude is preheated to about 280 ºC before sending it to crude furnace. Due to fouling of exchangers in preheat train (PHT) of Crude distillation unit (CDU), Furnace Inlet temperature decreases over the period gradually. This needs extra fuel firing in the furnace to maintain the required Coil outlet temp (COT). To maintain the crude preheat some of the exchanger is cleaned by bypassing the most fouled exchangers during running of unit. However it disturbs the heat integration, other operating parameters and reduction of unit t'put as well.

Based on analysis of the trend it was found that there is drop of crude preheating 8-10 oC per annum, which is equivalent to fuel 2500 SRFT/year. After exploring with various options for chemical treatment, it was decided to go for Antifouling chemical dozing program. Crude Antifoulant chemical basically disperse the Asphaltene to avoid deposition in tube surface and passivates the active metal surfaces to reduce the coking reaction in the exchanger tube surface. With minor modification at field, the chemical dozing was started last year, at downstream of the Pre- flash column. Post anti-foulant dosing it has been observed that the preheat drop rate reduced. We are successfully achieving FIT drop 0.5 Deg C/ 6 months. Thus the dosing of the antifoulant has increased the run length between exchanger cleanings and there is reductions in annual fuel consumption.

The case attempts to illustrate an application of the technique in CDU preheat circuit giving insights into the underlying principles, general methodology, data required for applying the technique and its merits on the increased operational efficiency and savings.

INTRODUCTION

Crude Management Program for overhead corrosion control program for Crude and vacuum distillation unit are put in place. The comprehensive chemical treatment is an operational practice and a process requirement to control the pH of the desalted brine water , minimize Salt content in crude, minimize iron and chlorine in process sour water .

Preheat and Exchanger Train fouling

Fouling in CDU VDU unit encompasses several aspects. In the feed exchangers, fouling is related primarily to the type of feed (asphaltenic, paraffinic) and to the history of handling prior to processing. The deposits typically found in crude feed exchangers consist of both organic and inorganic compounds. These deposits are found primarily at temperatures between 300oF and 500oF (150oC – 360oC). As the feed temperature rises above 300oF (150oC), water is evaporated and the inorganic salts reach saturation. These salts then begin depositing on exchanger surfaces. Organic deposits (which is carbon (C) with some amount of Oxygen (O), Sulphur (S) and Iron (Fe)), primarily asphaltenic compounds, will deposit as a result of blended condensates, recycle of highly paraffinic streams or by settling once they can no longer be held in solution. Those asphaltenes that are soluble in benzene are the lower molecular weight compounds naturally occurring in the feed while those not soluble in benzene represent the high molecular weight materials together with products of oxidation formed during transportation

The particulates and corrosion products such (FeS_2, Fe_3O_4), salt ($CaSO_4$) and sand (Si, SiO_2) are the inorganic compounds in the foulant sample collected on the surface of the organic deposits as well as settle out in the low velocity areas or are present as a direct result of corrosion. The fact that these inorganic materials are dispersed through most deposits makes it difficult to initially determine the sequence of fouling.

At operating temperatures below 300oF (150oC), the foulants are primarily a result of particulate material dropping out of the process stream. Corrosion is more prevalent in this section because of the presence of water as an emulsion, in solution, or as a separate phase. Sludge is also prevalent in this section, also separating from the bulk stream in areas of low velocity.

Organic fouling can be controlled by the use of antifoulants. Since most of the organic deposits will be in the form of sediment and asphaltenes, so the use of a dispersant type is suitable.

Four different effects are recognized for such depositions. One or more of these mechanisms would describe the organic depositions that may occur during refining.

Fouling due to Paraffins

Paraffins are normally stable at relatively low temperatures but are very deleterious at high temperatures. It undergoes thermal degradation, producing olefinic intermediates then condensation and cyclization ultimately leading to fouling that deposit on the heat transfer area.

Known Mechanisms of Deposition

The degree of dispersion of heavy organics in crudes depends upon the chemical composition of the petroleum. The ratio of polar/non-polar and light/heavy molecules and particles in petroleum feedstock (Figure 1) are the factors primarily responsible for maintaining the stability of the poly-disperse oil mixture.

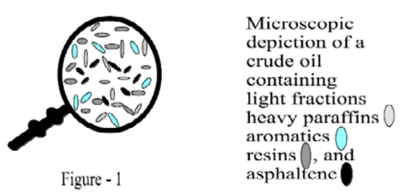

Figure - 1

1. Solubility Effect

Deposition of heavy organics can be explained by an upset in the polydisperse balance of petroleum feed composition. Any change in temperature, pressure or composition may destabilize the polydisperse oil. Then the heavy and/ or polar fractions may separate from the oil mixture into micelles, another liquid phase or into a solid precipitate. Segments of the separated fractions which contain sulfur, nitrogen & or hydrogen bonds could start to flocculate and as a result produce the irreversible heavy organic deposits which may be insoluble in solvents.

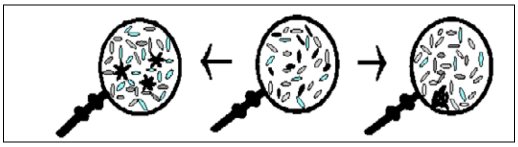

Figure 2: Micellization of asphaltene due to increase in aromacity and asphaltene precipitation due to increase in light paraffin content of oil

2. Colloidal Effect

Some of the heavy organics (especially asphaltenes) will separate from the oil phase into an aggregate and then will remain suspended in oil by some peptizing agents, like resins, which will be adsorbed on their surface and keeping them afloat as demonstrated in Figure 3.

Stability of such steric colloids is considered to be a function of concentration of the peptizing agent in the solution, the fraction of heavy organic particle surface sites occupied by the peptizing agent, and the equilibrium conditions between the peptizing agent in solution and on surface of heavy organic particles. The amount of peptizing agent adsorbed is primarily a function of its concentration in the oil. A concentration variation of a peptizing agent (e.g. resins) in oil will cause its adsorbed amount on surface of heavy organic particles could take place due to the change in their chemical-potential balance between the bulk oil phase and the surface phase as shown in Figure 3

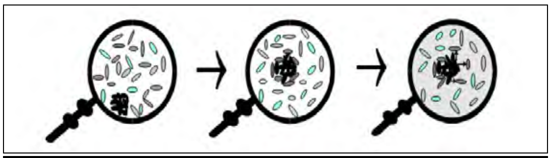

Figure 3: Peptization of ashpaltene precipitators by resin to form steric colloids and migration of resins from ashpaltene surface due to increase of concentration of light paraffin content of oil

3. Aggregation Effect

The peptizing agent concentration in oil may drop to a point at which its adsorbed amount would not be high enough to cover the entire surface of heavy organic particles. This causes the potential for aggregation of heavy organic particles due to

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development of free active sites on their surfaces and their eventual flocculation as shown by Figure 4. This may then permit the heavy organic particles to come together (irreversible aggregation), grow in size, and flocculate. The nature and shape of the resulting aggregates will determine their effect on the behavior of the petroleum feeds.
Various aggregating macromolecules follow different aggregation patterns.

Figure 4: Aggregation and growth of heavy organic colloids and their eventual deposition

4. Electro-Kinetic Effect

When petroleum oil is flowing in a conduit there is an additional effect to be considered in the behavior of its heavy organic constituents. This is because of the development of electrical potential difference along the conduit due to the motion of charged particles. This Electrical potential difference could then cause a change in charges of the colloidal particles further down in the pipe, the ultimate result of which is their untimely deposition and plugging of the pipe. *The factors influencing this effect are the electrical and thermal characteristics of the conduit, flow regime, flowing oil properties, characteristics of the polar heavy organics and colloidal particles and blending of the various petroleum feeds.*

Crude analysis result initial and presently

(Table 01)

Assam crude assay results	2019	1999
Density	0.8856	0.8706
Carbon residue, % wt	2.7	1.95
Asphaltene content, % wt	1.07	0.55
Salt content, PTB	0.90	0.0146
Water content, % vol.	0.6	0.6
Total acid number, mg KOH/g	0.380	0.53
Trace Metals, ppm		
Iron	36.1	17.5
Nickel	7.94	0.3
Copper	1.52	0.2
Vanadium	<1	0.2

Depending on the kinds of operation and the heavy organics present refer table 01, one or more of the effects described above will be responsible for heavy organics deposition.

Crude Pre-Heat Fouling Control Techniques at Refinery

- Control caustic addition upstream of preheat train to limit contribution to fouling
- Reduce pH of desalter wash water to 5.5.
- Use desalting chemicals with solids wetting properties.
- Slop oil treatment to dehydrate and to remove solids.
- Eliminate mixing of light parrafinic crude oil with asphaltenic crude oil
- Use Chemical Additives as Fouling control approach

Benefits of using a Fouling Control Program Fouling Costs shall come down wrt:

- o Higher natural gas or fuel oil consumption
- o Reduced equipment life
- o Premature equipment life
- o Reduce runs between shut downs
- o Production interruptions
- o Degraded product quality
- o Revenue shortfalls
- o Failure to meet contracts
- o Increased maintenance costs
- o Increased catalyst costs
- o Reduced profitability

Fouling control program Benefits by doing away the above costs

Steps adopted for Fouling Control Technology:

i) Unit Survey
ii) Identify Foulants
iii) Establish Mechanisms
iv) Operational Modifications
v) Fouling Control Additive Program
vi) Monitoring Techniques
vii) Economics

The increased profit possible with antifoulants includes an increase in production, fuel savings, maintenance savings and other savings due to greater operating efficiency.

In the refinery crude unit where PHE EEs fouling requires that the crude unit furnace be fired at a higher rate to produce the same furnace COT. Here, typically, the increased fuel necessary would be 270,000 BTU's per 1000 barrels for each degree (F) of temperature loss. Considering that fuel today costs from $0.50 to $2.50 per million BTU's, fouling can increase fuel costs as high as several hundred thousand dollars a year. For NRL, if a 65,000 barrel-per-day loses 60oF(15oC) of preheat temperature in six months, about an additional $200,000 would be spent on fuel over the six month period (assuming a fuel cost of $1.50 per million BTU's). Essentially, this is needlessly lost money.

Generally this also causes through put loss & throughput must be reduced about three barrels per day per 1000 barrels of charge for each degree of FIT loss. In the scenario cited above, approximately $ 800,000 would be lost in six months (assuming $0.50 profit per barrel of crude oil).

Data Analysis:

Detailed analysis to identify the temperature drop and other operating parameters that affects the PHT performance was carried out.

Following summary table highlights the FIT drop observed in the PHT over a period of six months.

Date	Crude Flow, m3/hr	Desalter Temp	FIT	delta preheat	TOTAL Approach enthalpy after desalter
05/14/2015 8:00 05/18/2015 8:00	229.2624	124.6922	281.9704	157.3	325602.6
05/26/2015 8:00 05/29/2015 8:00	400.69175	123.57325	283.2165	159.6433	473526.8214
06/11/2015 8:00 06/14/2015 8:00	404.907	122.0985	279.7285	157.63	495219.242
06/22/2015 8:00 06/25/2015 8:00	448.328	124.644	279.161	154.517	524617.297
07/14/2015 8:00 07/17/2015 8:00	442.419	121.6705	277.6535	155.983	535076.335
09/01/2015 8:00 09/05/2015 8:00	434.0644	122.961	278.0906	155.1296	523042.5839
09/23/2015 8:00 09/26/2015 8:00	306.836	122.49575	281.0213	158.5255	416103.8709
10/16/2015 8:00 10/20/2015 8:00	424.6576	124.9942	278.5776	153.5834	516618.4754
12/06/2015 8:00 12/09/2015 8:00	381.2165	120.74525	277.0773	156.332	479092.6484
12/22/2015 8:00 12/25/2015 8:00	377.0175	117.04675	278.2823	161.2355	483673.1301
01/01/2016 8:00 01/03/2016 8:00	362.0743333	124.0053333	276.0093	152.004	458950.2858
01/22/2016 8:00 01/26/2016 8:00	420.63	118.54	274.06	155.52	509934.82

Recommendation

Based on the data analysis ,testing in our central laboratory in Noida, and study, it was decided to go for high temperature antifoulant additive which is a combination of dispersant and metal chelator for the PHT, at a <u>dosage of 5 to 6 ppm</u> based on crude flow rate @430m3/h.

Normally starting the antifoulant treatment program with clean exchangers, better performance with the antifoulant program is expected. This will offer surface passivation and metal passivation and helps in arresting the corrosion.

Salient features of typical Antifoulant:-

- ✓ Antifoulant contains Dispersant, Metal Deactivators & Coke Suppressants components.
- ✓ High Temperature Stability – Onset of thermal decomposition >380 degC
- ✓ Increased Polymer active sites (more polymeric arms)
- ✓ Increased charge sites to provide better attraction

Expected Key Performance Indicator (KPI)

Normalized Furnace Inlet Temperature (NFIT) is a concept of monitoring FIT that gives proper guidelines to study/analyze the performance of PHT. Just by checking day to day FIT values only and based on that deciding the performance could be misleading. Since, the performance of PHT and FIT depends on flow rates, desalter temperature, approach enthalpy of heating media and other operating parameters; we suggested monitoring FIT based on flow weighted average FIT and data points where operating parameters are comparable.

Injection Location:

It was decided for the injection location at the downstream of flash drum (upstream of exchanger EE011). Facility of slip stream and injection quill provided for proper dosing.

Application & monitoring:

For the application of chemical, field operator is entrusted to monitor and ensure dosage rate at recommended level, collection of data on day to day basis. Data analysis, daily reporting on day to day basis on performance improvements of the program is being carried out.

<u>Cost Benefit analysis</u>:Table 2.0

ROI Calculation for PHT Antifoulant		
	Temp (deg C)	Enthalpy (MM kcal/hr)
	COT: 370	90.25
	CIT: 280*	57.79
	CIT: 277*	56.96
	Enthalpy (MM kcal/hr)	
Heat duty from 280 deg C to 370 deg C	32.46	MM Kcal/hr
Heat duty from 277 deg C to 370 deg C	33.29	MM Kcal/hr
Enthalpy difference from 280 to 277	0.83	MM kcal/hr
Considering 90% efficiency	0.9222	MM kcal/hr
	922222	kcal/hr
	92.222	Kg/hr

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	737.78	T/yr
Fuel Oil Cost	20000 T/yr	
Rs. Total cost saved 14755555.56 Rs./yr		
Treatment Cost(Approx.)	4500000	Rs/yr
Net Savings	10255555.56	Rs/yr

**Considering FIT drop reduced to 3 deg C from present drop of 6 deg C, i.e. 50 percent improvement in FIT*

PHT data analysis and study :

Methodology:

1. The Crude sample is tested at our R&D lab in greater Noida to study the fouling potential of the crude and based on the lab analysis, suitable antifoulant is screened and dosage is estimated at lab.

2. PHT data is analyzed by studying the FIT trends, desalter temperature, approach enthalpy of heating media, delta preheat temperature across the PHT.

Tools to Monitor

Antifouling application:

To monitor the antifoulant application, there are a number of tools and techniques that are advised:

- ✓ Microscopic Evaluation
- ✓ HLPS (Hot Liquid Processing Simulator)
- ✓ Thimble Rating
- ✓ Asphaltene Dispersancy Test
- ✓ OCM (Oil Compatibility Model)

Post Antifoulant Treatment:

- ✓ Field Monitoring of Heat Exchangers – Temp & Pressure Survey
- ✓ Laboratory analysis – Filterable solid
- ✓ Laboratory analysis – HLPS on Treated Crude & detailed analysis of foulant recovered during exchanger cleaning.

HLPS Tests:

This will give an idea about Fouling of samples (crude) which can be compared with past data.

Detailed Foulant Analysis of the sample collected from Preheat Exchanger during Cleaning

Inspection:

Such analysis provides vital information on following:

- ✓ Fouling mechanism and fouling precursors
- ✓ Whether inhibitor is providing desired fouling control, i.e. if product is Asphaltene dispersant, whether Asphaltene % has reduced in foulant or not.

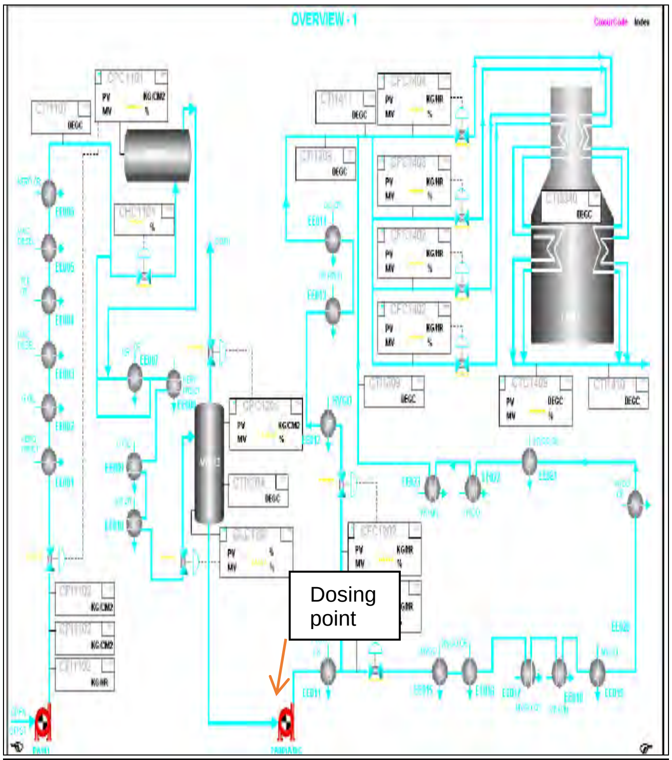
Field Monitoring of Heat Exchangers:

- ✓ Heat Transfer rate & Fouling Factor of Individual Exchangers ***by Temperature Survey***
- ✓ We can find out the exact fouling location (Shell side or Tube side) in exchangers ***by Pressure survey.***

Filterable Solid analysis:

Filterable solids are non-polar compounds. Filterable solid analysis in Crude is also important because it (mainly FeS) often provides a nucleus for the formation of adherent organic deposits & the organic deposits further polymerize/dehydrogenate on the hot metal surfaces of the heat exchangers.

Graphics snapshot of dosing point at CDU VDU- NRL, Assam.



We have started Crude Antifoulant program from Dec’18. Dosage was started from 20th Dec’18. Dosage has been stabilized to 5 PPM. We have

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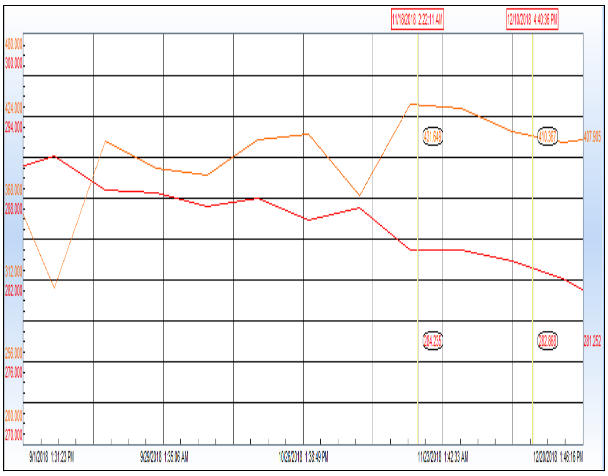
started our superior technology Crude Antifoulant ,a high temperature Antifoulant additive which is a combination of dispersant and metal chelator. This analysis will capture the benefits of Antifoulant which will help to tackle the drop in FIT.

Performance summary:

Parameters	Baseline (1st Jan'19 to 7th Jan'19)	31st Jan, 2019	28th Feb, 2019	31st Mar,2019
Crude Flow rate, m3/hr	417	367	395	306.2
Flash drum bottom temp, deg C	175.9	176.3	170.7	178.6
Delta preheat temperature, deg C	103.6	105.1	107.6	104.3
FIT, deg C	279.7	281.4	278.3	283
NFIT, deg C	279.6	281.5	278.32	282.9
Drop in NFIT		No Drop compared to Baseline	1.28 deg C drop compared to Baseline	No Drop compared to Baseline
NRL KPI		2.5 deg C drop in NFIT/6 Months		

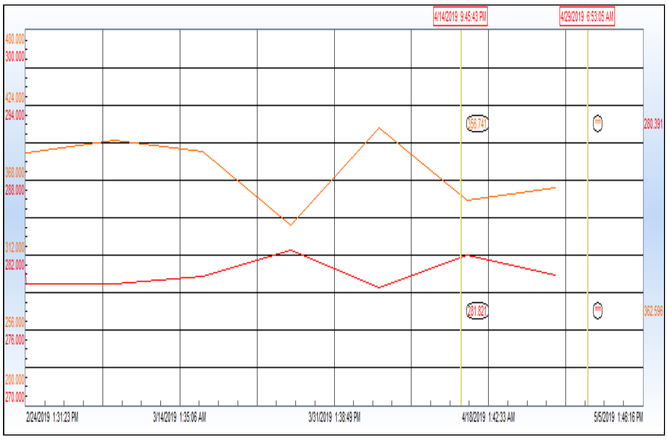
Overall the performance is steady when compared to baseline.



Pre-Antifouling dosing period: Feed flowVs Preheat temp

References:

IP 143/90 (ASTM D3279-90) "Asphaltene (Heptane Insoluble) in Petroleum Products



Post-Antifouling dosing programme: Feed flowVs Preheat temp

Bottom Line:

The refinery calculated $3 million in annualised fuel savings after subtracting treatment costs.

Performance Observation:

The operating data has been analyzed and ran process stream simulations to develop a treatment program that delivered more than 70 percent fouling control efficiency, increasing unit throughput and dramatically reducing fuel consumption.

Benefit Summary:

Refinery calculated $3 million in annual fuel savings.

Delivered more than 70 percent fouling control efficiency and improved exchanger performance.

Furnace Inlet temperature was maintained at higher rate and stabilized.

Increased unit throughput and drastically reducing fuel consumption.

Refinery was able to avoid downtime and costly, hazardous heat exchanger cleaning.

ENERGY EFFICIENCY AS A SERVICE: INDIAN ESCO MARKET ASSESSMENT - RECENT TRENDS, DRIVERS AND BARRIERS

Shravani Itkelwar[1], Deepak Tewari[2]

[1]*Industrial Energy Efficiency and ESCO & Financing*
Alliance for an Energy Efficient Economy
New Delhi, India
shravani@aeee.in

[2]*Industrial Energy Efficiency and ESCO & Financing*
Alliance for an Energy Efficient Economy
New Delhi, India
deepak@aeee.in

ABSTRACT

Energy service companies (ESCOs) have been instrumental in making energy-efficient technologies and services accessible to end-users in market segments which normally doesn't consider or are able to afford such capital-intensive projects. As part of a pan-India survey of ESCO market, wide-scale market research and analysis was carried out. The paper presents the industry trends of the Indian ESCO market like solutions offered, empanelment status, sectors served, ESCO business models in the year 2018-19. The shared savings is the most preferred business model by end-consumers across sectors. Energy efficiency solutions related to HVAC, lighting, motor, pump, drive, fan had major share while boiler, solar, IoT based, waste heat recovery, power quality improvement related solutions contributed less to the ESCO business. The strongest growth is experienced in the buildings and large industries sector while market penetration slacked in the SME and public infrastructure sector.

The paper highlights the most important drivers and market barriers with sector-specific indications derived from primary and secondary research. As of today the EE market is being driven by key government initiatives like PAT scheme, risk guarantee funds, innovative programmes by Energy Efficiency Services Limited (EESL) etc. The main barriers to the energy service business are access to finance by low grade ESCOs, lack of awareness for EE measures, adherence to energy service performance contract etc. Designing of innovative financing mechanisms, dissemination of best practices leading to increased demand for EE projects and robust framework for enforceability of contracts etc. will lead to scaling of energy service market.

Keywords— ESCOs, Market Development, EE-as-a-service, Market Evolution

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INTRODUCTION

The growing energy demand, energy security and need for climate change mitigation led to the integration of energy efficiency measures in all energy intensive activities. Unlocking the energy efficiency market calls for an urgent need of different players of the ecosystem like policy makers, energy service companies, financing institutions (FI's), end users to act in a manner, the combine output of which is an energy efficient economy. The Energy Service Company (ESCO) market in India is 300 million US dollar (IEA, 2017). Whereas the estimated market potential in India is anywhere between $10 billion to $35 billion (Kumar, et al., 2017). The ESCO market is at nascent stage in India with several challenges faced by each stakeholder involved.

As defined by Bureau of Energy Efficiency, *Energy Service Companies (ESCOs)* is a company that offers energy services comprising,

- design, retrofitting and implementation of energy efficiency projects after identifying energy saving opportunities through energy audit of existing facilities
- energy infrastructure outsourcing, power generation and energy supply
- assisting host entities in arranging finances for energy efficiency projects by providing a savings guarantee, risk management in the implementation of the energy efficiency projects

- measurement and verification(M&V) to quantify actual energy savings post implementation of energy efficiency projects [3].

Energy Performance Contract (EPC)

EPC is a mutual agreement between ESCO and energy user which includes the details of energy use or consumption pre and post implementation of ECMs, the method to calculate the energy savings, conversion of these savings to monetary value and thus transfer of monetary benefits to the ESCO as per mutual agreement before the implementation of ECMs. As the returns for ESCO are directly depended on the savings through ECMs, a mutually agreed measuremnet and verification protocol (M&V) is essential which clearly defines the calculation of savings through ECMs. Thus M&V, policy for purchase of equipment, its operation and maintenance, terms and conditions in case of equipment failure or in case of any dispute etc are an important component of EPC.

The BEE empanelment process provides ranking (grading) to energy service companies based on a set criterion on a scale of 1-5, with Grade 1 being the highest rank. However, the grading process has not been able to provide the other relevant information which are generally required by the Energy consumers, Bank, or Financing institution.

The various stakeholders involved in this ESCO ecosystem are energy service providers; energy efficiency technology suppliers; FI's; end users; policy makers; government agencies including State Development Agencies, multilateral and bilateral organisations.

METHODOLOGY

Based on the interactions with stakeholders of the ESCO community, it was identified that there is a need for detailed profiling of the energy service companies. The existing BEE empanelment system lacks information about the experience of the ESCO in terms of - delivering the implementation of the energy efficiency projects, sectoral experience, ECM categories, Ticket size, ESPC models, financing in projects, and banks/FI's handled in the past etc. To address the issues and to provide a clear/transparent picture to all the stakeholders, a brief survey was carried out e by Alliance for an Energy Efficient Economy (AEEE) to capture all the key information about the energy service companies which are most relevant and are generally enquired by the decision makers, energy consumers, policy makers, industry associations and financing bodies. Similar to profiling of the energy service companies, detailed profiling of the Banks or FI's was also done with an objective to provide relevant information to all stakeholders such as energy service companies, energy consumers, decision makers on the various financial products/ schemes available for undertaking the energy efficiency projects.

The following methodology was adopted to assess the energy service sector market :

1. Identification of ESCOs and FI's– A list of all the BEE empanelled 125 ESCOs along with 25 other ESCOs working in this domain but not covered in the BEE list was made to be part of the survey. The main focus of this survey was to identify the technical and business competencies of smaller ESCOs and understand various challenges being faced by them. Along with ESCOs, 7 FI's working in the energy efficiency domain were also identified.
2. Designing of template and capturing key information- For collecting the key information to analyse the existing scenario two templates were designed :

   Template for profiling of Energy Service Companies – Key information about energy service company i.e. sectors covered, top ECM categories, typical ticket size, typical payback period, mode of financing in past projects etc. was captured.

   Template for profiling of Banks & Financing Institutions - The survey form has been designed to capture all the key relevant information on the financial products / schemes and the experience of the bank/ financing institution such as - target sectors, EE loan size, collateral requirements, Interest rates, preferred loan period etc.
3. Reaching out to ESCOs and (FI's) – ESCOs and FI's were contacted via email, telephone and some were even reached personally to capture the required information. Few ESCOs were reluctant to share this information as they considered it a threat to their business. FI's were non responsive to the survey as only one FI participated out of the seven approached.
4. Analysing the data collected – 48 BEE empanelled ESCOs and 17 other ESCOs actively participated in the survey. The collected data was analysed to

get an understanding of the energy service companies for the service provided, empanelment status, sectors served, solutions provided etc. As only 1 FI participated in the survey, limited insight was obtained about the FI's working in energy efficiency space.

DISCUSSION AND RESULT ANALYSIS

Analysis of Energy Service Companies Profiles

Below is a short analysis based on what kind of services do the ESCOs provide, what area they serve to and what technology solutions are available with them.

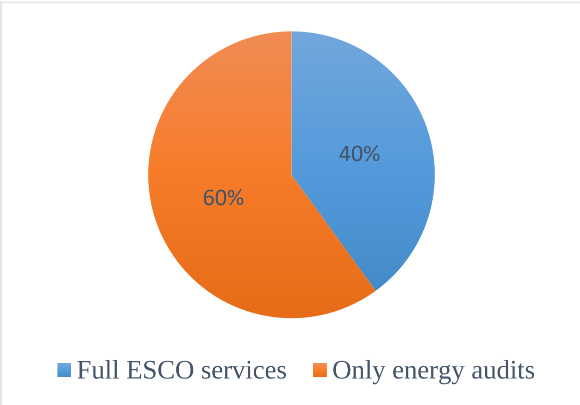

Figure 1: Type of Services Provided by ESCOs currently registered on ESCONet[1]

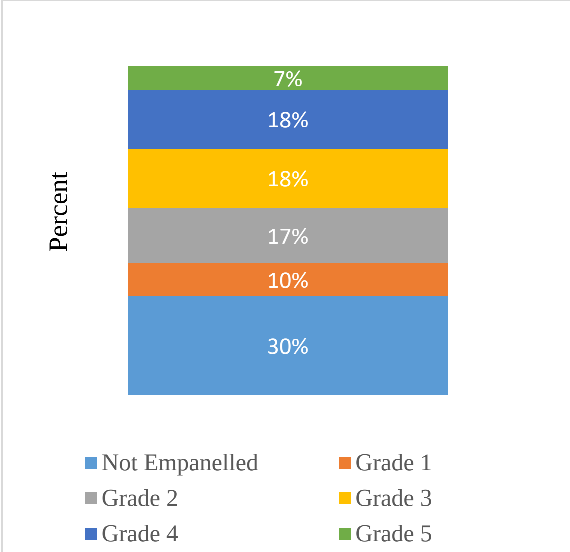

Figure 2 : Empanelment Status for ESCOs on ESCONet currently

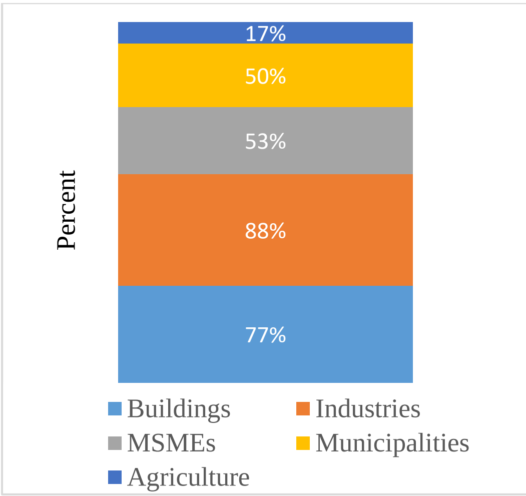

Figure 3 : Sectors being Served by ESCOs currently registered on ESCONet

[1] ESCONet is a web portal to bring together all the stakeholders of the EE ecosystem – Service and technology providers, startups, financing institutions, policy makers, end consumers, influencers etc. https://www.esconet.biz/

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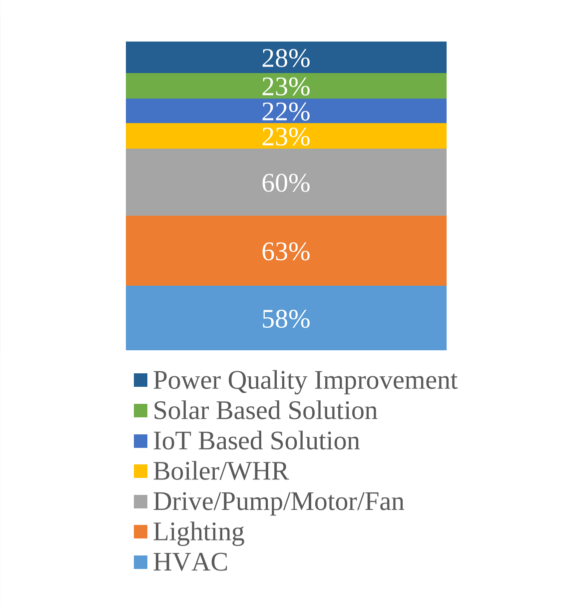

Figure 4 : Share of Solutions provided by ESCOs currently present on ESCONet

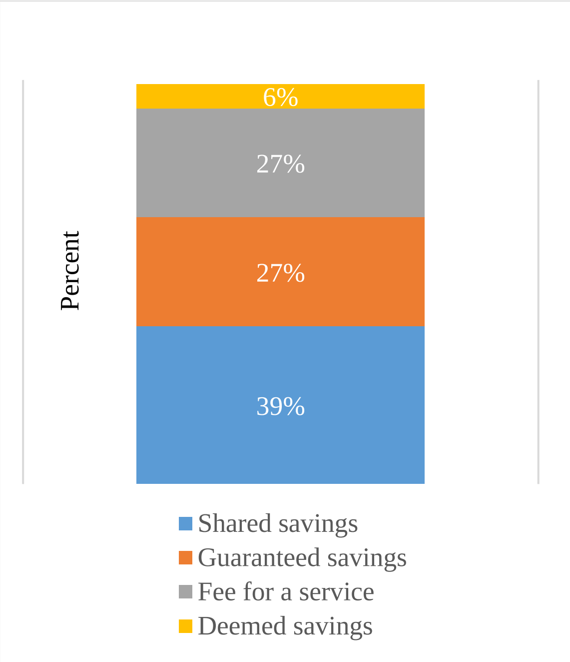

Figure 5: Share of business models implemented by ESCOs currently registered on ESCONet

Some of the key findings of the preliminary analysis, based on the profiles of sixty (60) energy service companies are as follows-

- The analysis shows that 30% of the energy service companies do not have BEE empanelment but have been working under Energy Savings Performance Contracting model and been providing range of ESCO services. The remaining 70% of ESCOs are graded in different categories by BEE as shown in Figure 2.
- Energy Conservation Measures (ECMs) like Lighting, Drives, Fans, Motors, Pump and HVAC are among the top services provided by energy service companies, while Power Quality Improvement, Boiler, Waste-Heat Recovery, IoT and Solar Based solutions are also prevalent in services being offered. It is observed that single ESCO is providing multiple solutions.
- Industries and Buildings are the two key sectors where major ESCO business is concentrated which is followed by MSMEs, Municipalities and Agricultural sector.
- The analysis also showed that 60% of the empanelled or non-empanelled energy service companies provide only energy audit services and not fully fledged ESCO service while only 40% provided full ESCO Services.
- Among the ESCO business models implemented, *shared savings* is the most sought after model followed by *guaranteed savings* and *fee-for-a-service* model.
- The typical payback period for ESCO projects implemented was 1 to 3 years and typical ticket size observed was approx. $15000 to $300,000 per project (AEEE, 2017).

Analysis of Banks & Financing Institutions Profiles

As per the limited profiles received and one-to-one interaction with some financing institutions, key findings were :

- Most of the banks are typically interested only in larger ticket size of project to avoid high transaction cost as their internal policy matter.
- Few banks have limited focus and considers loans only for manufacturing technologies, infrastructure related projects etc.
- The preferred tenure of loan for energy efficiency projects is three to five years.
- The ticket size of loan per EE project ranges from 60 lakhs to 15 crore.

Drivers : Key Government Initiatives

The Government of India enacted Energy Conservation Act (EC Act) in 2001 with the goal of reducing energy intensity of Indian economy. Bureau of Energy Efficiency (BEE), a statutory body under Ministry of Power is responsible for the implementation of the Act. BEE has formulated several policies/programs under the overall ambit of

EC Act for efficient use of energy and its conservation. The policies/programs that support energy efficiency drive & ESCO business model in the country derived from secondary research are-

- Perform, Achieve and Trade (PAT) is a market based mechanism, that mandates energy savings targets to designated consumers. The savings target provided to each industrial unit is based on its current level of energy efficiency. The PAT scheme opens the oppurtinities for ESCOs to engage with industries for meeting their compliance requirements of energy savings.
- Partial Risk Guarantee Fund for Energy Efficiency (PRGFEE) is risk sharing mechanism to provide commercial banks with a partial coverage of risk involved in extending loans for energy efficiency projects. PRGFEE guarantees 50% of loan amount or Rs. 10 crore per project, whichever is less. This guarantee is extended to financial institutions which will extend loans to ESCOs for implementing EE projects in buildings, municipalities, SMEs and industries.
- Venture Capital Fund for Energy Efficiency (VCFEE) provides equity capital to energy efficiency projects. It provides last mile equity support to specific energy efficiency projects, limited to a maximum of 15% of total equity required, or Rs. 2 crores, whichever is less. ESCOs working in buildings and municipalities are the key potential beneficiaries of the VCFEE.
- Formation of a super ESCO who has several flagship programmes like Domestic Efficient Lighting Programme (DELP), Municipal Street Lighting, Agriculture Demand Side Management (AgDSM), Buildings Energy Efficiency Retrofit Programme (BEERP), Partial Risk Guarantee Fund for Energy Efficiency (PRGFEE). These programmes have transformed the market of ESCO by overcoming the barriers in the existing market and thus providing innovative business models like Demand Aggregation, Pay-as-you-save etc. as a solution to the existing barriers.
- The Legal instruments like “Insolvency and Bankruptcy Code 2016” and “MSME Samadhaan- Delayed Payment Monitoring System” provides ESCOs the benefits to address their payment security related issues. The legal provisions strengthens the maximum credit period and higher penal interests if payments are delayed beyond a certain period.

Challenges for ESCO market

The stakeholders deliberation provided insights on the status of the ESCO business model and the key barriers to catalyse the ESCO market. The challenges faced by the energy service providers, energy users, policy makers, FI’s in undertaking the ESCO based projects as derived from primary and secondary research has been collated and presented next in order of their priority.

Barriers/Challenges for ESCOs

1. <u>Payment security risk</u>- The security on the investment is one of the biggest risks faced by the ESCOs at the moment. The Indian ESCO market is still at the nascent stage and most of the energy service performance contracts are signed on Shared Savings model as shown in Figure 5, which have an inherent risk of payment recovery as the entire investment is made by the energy service company. The adherence to contract and delayed / deferred payment from client poses serious risk to scale up the ESCO market.
2. <u>Banking transaction history and Collateral requirement</u> – Most of the energy service companies in India are start-ups or small businesses that do not have the large assets or a robust credit history which affects their possibilities to access finance. The ESCOs who have emerged over the past few years and attained a market credibility with FIs, manage to get the finance even without collaterals. However, the situation is very grim for the start-ups and new entry players who wish to work as ESCO.
3. <u>Transaction Cost</u> – The transaction cost is an additional cost component which is charged over and above the loan and the interest. In some cases like low ticket size project the transaction cost becomes too high and impacts the profitability of the project.
4. <u>Baselining</u>- An energy baseline allows the ESCO to compare energy consumption and performance before and after efficiency upgrades are implemented. Lack of sufficient data and inadequate metering infrastructure at client facility pose significant risk for the ESCOs in developing the baseline. ESCO

have to invest their long time and capital in capturing the operation of the facility to develop an accurate baseline.

5. Trust deficit- Many of the potential clients of energy service companies are still unaware of energy performance contracting business model and ESCOs. Lack of awareness, knowledge and trust in the ESCOs has severely hampered the demand of ESCO services.
6. Ticket Size – Most of the banks/FI's normally prefer large ticket size projects. This is the irony, as most of the energy efficiency projects especially in buildings and industries are of low investment value, and therefore ESCOs struggle to avail the finance.
7. Entity Appraisals – The banks / FI's perform due diligence process that includes entity and project appraisals before sanctioning of the loan. The entity appraisal is carried out for both ESCO and Client (where the EE retrofit is being undertaken) and sound credit rating for each of the entity is an indespensible criteria.

Barriers/Challenges to Energy Consumers

1. Lack of awareness – The energy users lack awareness on the benefits of energy efficiency measures like energy cost savings etc. There is a need for highlighting successful case studies/success stories of ESCO based energy efficiency projects in the public domain for all the sectors. The energy consumers are interested in knowing the energy performance benchmarks for their sectors/sub-sectors, technological solutions, energy savings potential and measurement & verification approach adopted for validation of energy savings. The case studies are an important resource to build trust about the technology / ESCOs for the retrofit.
2. Insufficient market drivers – Building owners and operators do not yet feel pressure to drive energy efficiency projects as the energy cost is not significant enough to concern the facility owners. There has been PAT regulations for some of the industries and hotel buildings however they are not very stringent and can be easily addressed by the facility owners themselves.
3. Lack of interest by ESCOs – The end consumers have pointed that the energy service companies are not interested in the smaller size projects.

Barriers/Challenges to Financing Institutions

1. Difficulty to understand energy savings - Energy savings are measured with the help of electricity bills, readings from meters etc. Banks find it difficult to understand how these savings are calculated and thus their conversion to monetary value.
2. Non-standardisation of technologies - In absence of effective standardisation of technology, FI's find it difficult to trust a technology, understand the savings, their conversion to monetary value etc. Thus a proper standardisation of technology is essential to maintain a consistent quality and gain FI's trust in the technology.
3. Shortfall of savings – The investment in energy efficiency project is recovered by the savings achieved post implementation of ECMs. In case when the expected savings are not achieved the amount needs to be recovered from the ESCO. The banks find it difficult to recover their amount in this case as the financial capability of ESCO is not strong enough.

CONCLUSION AND WAY FORWARD

1. There is a lack of awareness amongst Indian banks and financial institutions on the energy efficiency financing requirement of the industry. There is an immediate need for training programs of bank professionals to improve their knowledge and understanding of energy efficiency projects, energy saving calculations and M&V frameworks to enable them to conduct due diligence of EE projects.
2. The compliance to energy service performance contract (ESPC) is low between the host and energy service companies. Therefore, strong policy actions in terms of legal provisions are required for enforceability of the contracts. BEE to facilitate with other relevant ministries on the development of strong legal provisions that can address such issues within a reasonable timeframe.
3. The demand for energy efficiency project through ESCO route is very less. Innovation is required to create an aggregation of demand for the ESCO industry. A marketplace is required to bring all the energy efficiency

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stakeholders to a common platform to discover new oppurtinities of ESCO business and financing needs.

4. The ESCO projects are risky in terms when the actual savings falls short of the guaranteed savings and energy service companies has to compensate for the same. Innovative mechanisms such as Energy Savings Insurance need to be explored for smoother operation and closure of ESPC.
5. Risk Guarantee Funds like PRGFEE and VCFEE needs to be structured in a way to enable their access to Grade 3, 4 and 5 ESCOs. These ESCOs are small in size, have low transaction history, lack in collateral, are less experienced in availing EE finance etc. There is need to penetrate risk guarantee funds to these ESCOs to enable them to secure their bank loans and thus get access to EE finance.
6. Innovative financing schemes needs to be designed to address the barriers of collateral requirement, low ticket size project, entity appraisal requirement for loan eligibility etc.
7. Standardisation of technolgies will provide a confidence to FI on the energy saving benefits, which would facilitate easier sanctioining of loans to ESCOs. For these technologies banks could develpe simplified templates which will reduce the processing time for them and eventually lead to reduced transaction cost. Also the end users and financers are aware of the risks associated with standardised technology which will help in easy loan sanction.
8. BEE to recognise innovative EE interventions by ESCOs and facilitate dissemination of these EE measures through web platform, by rewarding respective ESCO etc. This will lead to awareness creation and increased demand for EE measures thereby benefitting ESCO business.
9. Existing policy measures promoting energy efficiency needs to be expanded to new sectors to create an increased demand for EE projects, and creating more oppurtinities for business models like ESCO.
10. Development of simplified self-assessment tools, which facility owners can access and evaluate the energy performance of their facilities and at the same time compare it with the similar type of an energy efficient facility to be facilitated by BEE.

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ePROJECT BUILDER: PROMOTING WIDER ADOPTION OF ENERGY SAVINGS PERFORMANCE CONTRACTS THROUGH STANDARDIZATION AND TRANSPARENCY

Shankar Earni, Philip Coleman, Elizabeth Stuart, Peter Larsen

Building Technologies & Urban Systems Division
Lawrence Berkeley National Laboratory
Berkeley, California, United States
SEarni@lbl.gov
PEColeman@lbl.gov
EStuart@lbl.gov
PHLarsen@lbl.gov

ABSTRACT

Energy savings performance contracting (ESPC) enables building owners to implement facility upgrades and reduce energy and water consumption (often with operations and maintenance expenses) using the resulting annual stream of cost savings to cover project installation and financing costs. The size of the international ESPC market is ~$30 billion per year and growing. However, ESPCs still face myriad barriers to achieving their market potential. Barriers include lack of data standardization and transparency, lost data, and inconsistent project performance monitoring. These barriers have limited stakeholders' ability to understand how projects perform. The inability to document and quantify past projects' success has led to skepticism, aversion, and unnecessarily high transaction costs. This work discusses a standardized approach to develop and document ESPCs through eProject Builder (ePB), which involves a simple Excel-based set of financial schedules combined with an on-line data archiving and tracking system. ePB enables standardized collection, calculation and reporting of project data in a way that promotes greater transparency of ESPCs to facility owners and other stakeholders. Specifically, the key benefits of ePB are that it (1) minimizes redundancies; (2) eliminates data inconsistencies resulting from multiple data repositories; (3) increases transparency by preserving and providing access to data in perpetuity; (4) enables development of "what if" scenarios; and (5) standardizes data to allow for comparative analysis of ESPC projects. Accordingly, ePB increases confidence in the ESPC vehicle among prospective customers. The paper demonstrates one key aspect of ePB's value by using it to conduct sensitivity analyses of key factors in hypothetical ESPC projects.

Keywords—ESPC, EPC, Performance Contracting

INTRODUCTION

Energy efficiency is a cost-effective strategy to reduce the operational costs of facilities and lower environmental impacts while also promoting economic growth. In addition to generating annual energy savings, investments in energy efficiency mitigate the need for some amount of generation, transmission, and distribution infrastructure that would otherwise be needed to keep pace with accelerating demand (McKinsey 2009). The International Energy Agency (IEA 2006) estimates that, on average, an additional one dollar spent on more efficient electrical equipment, appliances and buildings avoids more than two dollars in investment in electricity supply, which is particularly valuable in economies like India where lack of capital is a major issue. Further, investing in energy efficiency retrofit projects can generate significant returns for investors while minimizing their risk. According to some, energy efficiency projects can provide—on average—a 17% internal rate of return (McKinsey 2008). Despite the high potential for energy efficiency to generate favorable returns, a significant number of barriers exist that hinder greater deployment of energy efficiency projects. Sorrell et al. (2000) compiled a list of barriers and categorized them as either economic, organizational, or behavioral. Economic barriers include: (1) limited access to up-front capital needed to implement many types of energy efficiency measures; (2) lack of data about past efficiency project performance, which could inform decision-making; and (3) uncertainty about whether a proposed project can provide sustainable long-term savings. Decisions based on incomplete or inaccurate information might result in cost-effective energy efficiency opportunities being missed or projects that may not realize the necessary savings.

A study conducted by Johnson Controls and the International Facility Management Association (IFMA) (Institute for Building Efficiency 2011), found that the barriers to energy efficiency in India are consistent with barriers in the United States: lack of technical expertise to identify retrofit opportunities; limited capital availability; uncertainty regarding projected energy and cost savings of proposed projects; and "insufficient" payback as decision-makers in India require a more rapid payback (often less than two years) (Delio et.al 2009) compared to a global average of 3.1 years (IFMA 2010). Despite these barriers, there is an enormous potential for energy savings in India—estimated at 183.5 billion kWh per year (Delio et.al 2009).

Energy service companies (ESCOs) engage in energy savings performance contracts (ESPC) as a key mechanism to help overcome barriers and promote investment in energy efficiency. ESPCs involve long-term contracts between customers and ESCOs that enable the customers to pay for energy retrofit projects with little to no up-front capital. ESPCs leverage private-sector financing dollars and enable the customers to pay for implementation of energy, water, and cost saving upgrades in existing facilities out of the multi-year stream of annual cost savings, which the ESCOs guarantee. Thus, the ESCO assumes some level of project performance risk, as specified in the performance contract. It should be noted that ESCOs provide a range of non performance-based energy services as well (e.g., construction bid-to-spec, fee-for-service, energy commodity procurement, consulting). However the literature generally defines ESCOs as companies that engage in performance-based projects as a core business and that assume some level of financial risk for those projects (Hopper et al 2007, Marino et al. 2010, Larsen et al. 2012). Delio et.al (2009) studied the ESCO industry in India and discovered that ESCOs there are classified into three categories: (1) a general ESCO (owned or operated by an equipment manufacturer or an energy supplier); (2) a vendor-driven ESCO (affiliated with an equipment or control manufacturer); and (3) a consultant ESCO (company that offers recommendations to a client based on knowledge or specialization). Eight ESCOs identified themselves as vendor-driven ESCOs, while 16 identified themselves as general ESCOs. No ESCOs classified themselves solely as consultants. The vendor-driven ESCOs earned 53% of the 2007 industry revenues. Ten of the 24 surveyed ESCOs indicated that they operated only through a guaranteed savings model; five operated only through a shared savings model (ESCO finances the projects and shares the operational savings with the customer) and the remainder used both.

ESCO INDUSTRY

The international ESCO industry market is growing quickly and now appears to be in the range of $30 billion per year (IEA 2017). ESCOs in North America and some Asian and European countries have been implementing performance-based energy efficiency projects in public- and private-sector facilities for nearly 30 years (Nakagami, 2010, Stuart et al. 2014, Bosa-Kiss et al. 2017). The U.S. ESCO industry has experienced significant growth from over most of the past two decades. In 2011, U.S. ESCOs reported aggregate industry revenue of about USD $5.3 billion, with expected growth to USD $7.6 billion by the end of 2014. IEA reports the 2017 U.S. market size as USD $7.6 billion (IEA 2019). Projects implemented by U.S. ESCOs save an amount equivalent to 1% of annual U.S. commercial building energy consumption each year (Carvallo et al. 2015).

Larsen et al. (2017) reported estimated remaining potential of the U.S. ESCO industry under two scenarios: (1) a base case, assuming current business and policy conditions, and (2) a case in which the market was unfettered by a number of existing market, bureaucratic, and regulatory barriers. The authors define remaining market potential as the aggregate amount of project investment that is technically possible for ESCOs to implement based on the types of projects that ESCOs have historically implemented in the institutional, commercial, and industrial sectors. The estimate draws on ESCO executives' estimates of current market penetration in those sectors. The authors estimate that the base case remaining market potential is USD $92–201 billion. They estimate a remaining potential of USD $190–333 billion under the unfettered scenario.

80–85% of U.S. ESCO industry revenue has consistently come from the public and institutional market (municipalities, universities, colleges, schools, state and federal government, and healthcare entities such as hospitals) [Stuart et al. 2017]. The federal government and nearly all states have enacted legislation that enables public sector facilities to enter into long-term performance contracts (up to 25 years in the federal sector and between 10 and 30 years in the state/local sectors). Such legislation, and associated government technical assistance programs, have been key drivers of ESCO industry growth (Carvallo et al. 2019). In other countries where ESCO markets have experienced significant growth (e.g., China and some EU countries), such growth has similarly been enabled by a range of supporting policies (Vine 2005; Bertoldi et al. 2006; Hopper et al. 2007, Marino et al. 2010; Duplessis et al. 2012; Yang 2016; Boza-Kiss et al. 2017).

The performance contracting market in China has grown dramatically, from USD $4 million in 2001 to USD $4.4 *billion* in 2010 (Kostka and Shin 2013), to $16.8 billion in 2017 (IEA 2019). Chinese ESCOs face challenging barriers and have barely begun to tap a tremendous technical ESPC market potential (Kostka and Shin, 2013). The European Union ESCO market has also experienced modest to significant growth for many of the member states in recent years (Bosa-Kiss et al. 2017).

India's ESCO industry is still nascent, even though the first three ESCOs were organized in the early 1990s (with funding from USAID). The Indian ESCO industry grew steadily and significantly after 2003 from a low base of less than INR 500 lakhs (USD $1.0 million) in 2003 to INR 8,640 lakhs (USD $17.7 million) in 2007 (Delio et.al 2009) and USD $300 million in 2017 (IEA 2019).

Obstacles for ESPCs

Despite steady growth over most of the past three decades, the U.S. ESCO industry has a long way to go to achieve its USD $100+ billion technical market potential. A range of market and institutional barriers continue to inhibit ESCOs and their customers (federal, state, and local agencies; educational institutions; and private commercial facility owners) from achieving the market potential and capturing the associated energy savings. A lack of data standardization, non-transparent approaches to project development, data losses over the term of a performance contract, and inconsistent project performance monitoring have limited stakeholders' ability to conduct timely analysis and accurate reporting of costs and savings to ultimately determine if the projects save money. This inability to document and quantify past projects' success has led to skepticism and unnecessarily high transaction costs, and in many cases, prevented proposed projects from moving forward. Some U.S. entities are actively calling for solutions to these barriers. For example, U.S. government audits critical of ESPC projects have recommended collecting and providing access to accurate data on these alternatively financed energy projects (e.g., see U.S. GAO, 2017).

Bhattacharjee et al. (2010) identified some of the barriers for implementing ESPC in the private sector and categorized them into four categories—market, institutional, financial, and technological. Ghosh et. al (2011) rank-ordered the barriers according to their importance, based on interviews conducted with staff at architecture, engineering and construction firms. The most critical barrier identified by the respondents was the lack of awareness about ESPC among the facility owners. Owners were not conscious about the energy efficiency potential of ESPC primarily due to information gaps, managerial disinclination, and lack of interest. Bhattacharjee et al. (2010) found that ambiguity between the owner and ESCO regarding realization rates of the estimated savings presented a barrier. The ambiguity relates to the credit risk, and perceived technical risk on the part of the facility owners, not only with regard to the savings realization of the measures, but also concerning the operating and maintenance risks for the installed equipment.

Financial barriers to increasing ESPC deployment include high transaction costs associated with paperwork requirements, and administrative and legal activities developing these contracts. These requirements can add costs to the project that the ESCOs may not be able to recuperate, so ESCOs may build in extra overhead to cover such transaction costs. For these reasons, as well as the savings guarantees they usually provide, ESPCs can be more costly per square foot than traditional design-bid-build type projects. Most private sector facility owners are not willing to pay the premium for ESCO-implemented projects compared to traditional design-bid-build type projects. Further, the private sector tends to focus its capital investments on implementing measures that have shorter payback periods (1–2 years) and that can meet specific internal rate-of-return requirements. Since they typically avoid implementing measures with longer payback times, they miss out on "deep savings" opportunities. Finally, the ESCO model's use of external financing presents another barrier to ESPC in the private sector. Financing energy efficiency might limit a private sector business owner's borrowing capacity that would otherwise be needed for funding the company's core business activities (Bhattacharjee et al. 2010).

Public Sector

The U.S. Department of Energy's Federal Energy Management Program (FEMP) and other federal, state, and local government agencies implement programs and disseminate tools, resources and training on ESPC. Despite these efforts, many stakeholders still consider ESPC to be cumbersome, unwieldy, and somewhat complex relative to traditional construction procurement processes. A survey conducted by Hopper et al (2005) found that the most often cited barrier to scaling up ESPC, particularly for the federal government, is the significant length of time it takes to develop projects (i.e., the time from when proposals are requested to contract signing with the ESCO). Most survey respondents indicated that ESPC project development times ranged from 12 to 24 months. This finding is consistent with another study (Hughes et al. 2003) that reported an average ESPC project development time of 14.9 months for projects initiated nearly 20 years ago. Another key barrier identified in the U.S. federal sector is the lack of appropriate and knowledgeable federal personnel to administer and manage these contracts through their entire life cycles, which may last as long as 25 years (GAO-15-432 2015).

The 1992 Energy Policy Act authorized the U.S. federal government to enter into long-term ESPC contracts (Congressional Research Service 2010). However, very few ESPC projects were initiated after its passage, due to extremely high transaction costs involved in negotiating every aspect of every contract. FEMP thus established the first indefinite delivery, indefinite quantity (IDIQ) contract vehicle in 1997. The IDIQ is a master contract that allows federal agencies to work with a prescribed set of pre-qualified ESCOs. The IDIQ contract has helped streamline ESPC procurement to some degree; between 1997 and 2017, 37 agencies used the IDIQ to award 369 projects across all 50 U.S. states (FEMP, 2017).

Frequently cited barriers to broad use of ESPC in the municipal,state, university/college, K-12 schools and healthcare (MUSH) market sectors include:

- Complicated procurement process resulting in long project development time and high transaction costs
- Lack or loss of data for existing projects that are still under contract and being paid off (data losses are exacerbated by staff turnover through the performance period)
- Lack of data standardization and inability to conduct analysis on past projects, or to compare projects across ESCOs and market segments
- Inadequate data to make the business case for ESPC
- Inability to institutionalize knowledge about ESPC best practices (Dasek 2017)

International

Several studies (Vine 2005, Westling, 2003a, Westling, 2003b, Bertoldi et al., 2003, Biermann 2001, Singh 2010) have focused on identifying the barriers associated with ESPCs in an international context. While there are impediments that are unique to each country, several are common across different countries including:

- Lack of information and understanding of the opportunities that energy efficiency and ESPCs offer
- Public procurement rules for ESPCs are non-existent in most cases and highly complicated and burdensome administratively
- Limited understanding of energy efficiency and ESPCs by financial institutions results in less capital financing available for energy efficiency projects compared to traditional capital investments in the energy sector (e.g., power plants)

Furthermore, many energy efficiency projects are too small to attract the attention of large multilateral financial institutions. Finally, energy efficiency projects and ESPCs are perceived to be riskier than supply-side projects, because they are often non-asset-based investments with no tangible collateral.

E PROJECT BUILDER

The U.S. Department of Energy (DOE) recognized that public agencies and their ESCOs needed new tools to (1) transparently document ESCO pricing and savings estimates for these complex projects; (2) provide secure access to standardized data and long-term preservation of records in order to facilitate analysis and reporting of project performance over time; and (3) enable users to compare proposed projects against historical benchmarks by geography, ESCO, and market segment.

eProject Builder (ePB) is a system designed to address key barriers in order to increase the market potential for ESPCs. ePB is a secure, web-based data entry and tracking system for energy efficiency and on-site generation projects in the U.S. The project was developed and is maintained by Lawrence Berkeley National Laboratory (LBNL) with funding from DOE. ePB is composed of a simple Excel-based set of financial schedules combined with an online relational database and document archiving system.

More specifically, ePB allows ESCOs and their customers to:

- Develop project “what if” scenarios using standardized data and financial calculations. This feature enables the customer or ESCO to run financial scenarios based on various combinations of inputs to understand the cash flow implications of different project configurations.
- Easily manage, track, and report data on a portfolio of building retrofit projects—through the contract term and beyond.
- Preserve and quickly access project information, savings verification data, and additional documents in perpetuity.
- Generate project financial schedules, raw data for deeper analysis, and reports (tables, graphs) on project and portfolio performance. This feature allows customers to analyze project data across their portfolio of approved projects including a comparison of realized savings to projected savings.
- Use statistics generated from ePB to benchmark proposed projects against to improve customers’ ability to evaluate the price reasonableness of proposals for a number of key metrics, such as annual M&V cost as a percentage of annual savings, and project development cost as a percentage of the total project implementation price. Such information will empower COs and other government stakeholders to properly evaluate the cost- competitiveness of a number of different contract types.

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- Contribute to a growing national database of ESCO projects, allowing researchers to research key trends in this growing industry.

ePB comprises two main components: (1) a Microsoft Excel-based data upload template, which the ESCO populates and uploads to the online system; and (2) a web-based application where users upload and track their project financial metrics, estimated and guaranteed savings, verified measurement and verification (M&V) results, and other data.

Initial development of ePB involved extensive stakeholder input from FEMP, federal agencies, state agencies, and ESCOs on the types of information that would be most useful for ePB to collect and track. Over time, LBNL has updated this list of data fields and other features in response to requests from users.

During the first year after ePB's launch in 2014, FEMP, the DOE Office of Weatherization and Intergovernmental Programs (WIP), and the National Association of Energy Service Companies (NAESCO) embarked on a collaborative effort to promote the system to federal and state government officials. The effort included regularly scheduled introductory webinars, and customized presentations to teams (e.g., state officials and their pre-qualified ESCOs). Such presentations served both promotional and training purposes; seeing a full demonstration of the system helped potential users of the system understand first-hand how it worked, and, importantly, how it could benefit them.

Most of the initial projects entered into ePB were federal IDIQ projects as it was mandatory. However, ePB uptake ramped up slowly in the early years, particularly in the non-federal sectors. A few ESCOs in the federal sector immediately began using ePB in order to provide transparency and engender customer confidence in non Federal projects; however most ESCOs initially perceived ePB as a burden, rather than a value-added tool.

In order to gain industry acceptance, LBNL collaborated with its longtime partner, NAESCO. Since 2000, LBNL and NAESCO have collaborated on ESCO industry research. LBNL and the NAESCO leadership engaged with the ESCO industry on issues related to ePB over the course of two years. As a result, industry leaders ultimately endorsed ePB, and NAESCO requires that ESCOs applying for its national accreditation program, submit the requisite detailed project information into ePB.

The arrangement significantly impacted ePB uptake: from October 2018 through September 2019 the number of projects in ePB increased 73%, from 657 to 1,140. In addition, over time an increasing number of state government ESPC programs are requiring ePB, which further contributes to increasing uptake. Currently ePB contains 1,140 projects, representing total investment of US $9.6 billion and total contract guaranteed savings of US $17.7 billion. The database comprises 45% federal, 55% state, local and educational, and 5% private commercial/industrial projects.

The following section demonstrates the value for users in being able to develop sensitivity-based "what if" scenarios for their projects. We conduct a sensitivity analysis by plugging alternative assumptions into the Excel-based data upload template.

SENSITIVITY ANALYSIS

A number of financial metrics (e.g., contract term, net present value (NPV), internal rate of return (IRR) and payback time) are sensitive to key factors associated with an ESPC. These factors include (1) implementation price and interest rate; (2) recurring costs such as annual M&V and operation and maintenance (O&M) expenses; (3) energy and non-energy cost savings; (4) other factors such as utility escalation rates and payment frequency and timing. Some of these factors affect financial metrics more than others. It is important to understand the effects of these factors, so that a more informed decision on how to structure a project can be made. To illustrate sensitivities of different factors on ESPC cash flow, the authors elected to focus on NPV. NPV is computed from the stream of ESPC cash flows, using a discount rate to place greater value on near-term cash flows and relatively lesser value on those that are further in the future. We demonstrate the sensitivity analysis using a sample ESPC project. Key details are summarized in Table 1 below.

Table 1:Sample Project Details

ESPC PROJECT PARAMETER	BASE CASE ASSUMPTION	RANGE OF ALTERNATIVE ASSUMPTIONS
Total Amount Financed (Principal)	$6,460,167	
Discount Rate	5%	
Performance Period	10 years	
Study Period	25 years	
Project Interest Rate	5%	3.5%–6.5%
Escalation Rates	5%	3.5%–6.5%
Guarantee Percentage	90%	80%–100%
Year-1 Estimated Cost Savings	$871,698	

This table also indicates a few factors that are tested as part of this senstivity analysis, along with a range of values for each. The length of the contract is assumed to be 25 years, meaning the savings from the proposed ESPC would last for that time. The savings accrued in a given year by the customer is defined as the difference between the annual payments and the

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guaranteed costs savings. The NPV is applied on these savings over a period of 25 years with a discount rate of 5%.

Interest rates are, of course, one of the factors that can substantially affect the project financials and rate of return. Higher interest rates increase the total debt service paid over the term of the contract and therefore lower the NPV of the project. Lower borrowing costs allow for deeper energy savings by including additional measures with longer payback into a project that was not financially feasible with a higher interest rate. Interest rate depends on several factors including the credit worthiness of the ESCO and/or customer, risk profile of the project, rigor of M&V, and knowledge about ESPC from the lender. Some of these issues can be alleviated by adopting tools like ePB that offer increased transparency and standardization. Figure 1 shows the impact of interest rates on NPV for different payment options.

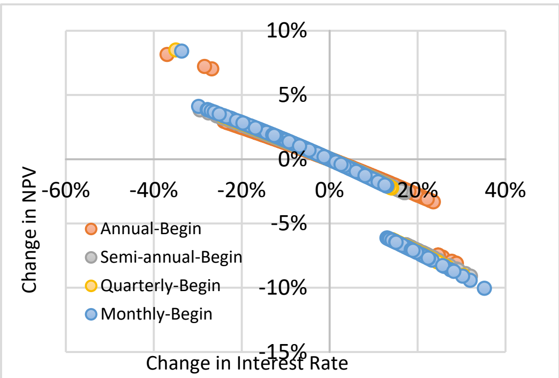

Figure 1: Project NPV as a function of interest rate.

As the interest rate increases, the NPV, for the project decreases underscoring that it is financially prudent to secure a low interest rate for ESPCs. The payment frequency and timing can also affect the NPV of the project (see Figure 2). An annual payment occurring at the beginning of the year tends to have the highest NPV, while the annual arrears payment has the lowest NPV. All of the other payment options have NPVs somewhere in between.

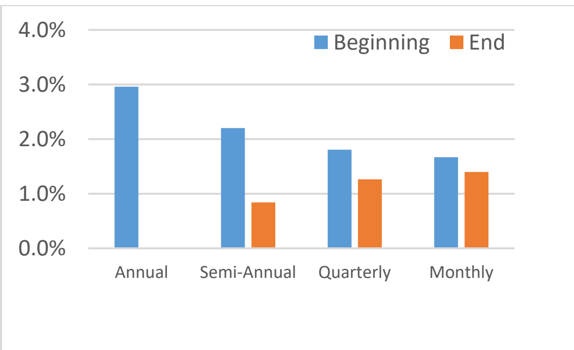

Figure 2: Effect in NPV of payment frequency and timing.

Escalation rates are applied to the utility (e.g., electricity) rates to determine the amount of monetary savings available from a project, given a guaranteed level of energy savings, to pay for the deal (i.e., its debt service and any project servicing costs, such as O&M or M&V). Financial metrics like NPV are extremely sensitive to the escalation rates. Choosing the optimal escalation rates is important, because selecting a rate that is less than the actual would be equivalent to leaving savings on the table and would result in paying more in total interest over the life of the contract than what is necessary. On the other hand, over-estimating escalation rates could mean that the project's monetary savings fall short of required payments

Figure 3 shows the impact of escalation rates on NPV for different payment options. As the escalation rates increase, the NPV for a guaranteed savings project increases almost proportionally, intimating that it is financially prudent to use a higher rate, assuming those rates are realistic/reasonable, which is a big unknown in any project. In the United States, the National Institute for Standards and Technology developed and manages an energy escalation rates calculator (EERC) that uses DOE's Energy Information Administration's energy prices (Coleman 2015). Because EIA has somewhat underestimated future energy prices in the recent past (since 2000), EERC estimates of escalation rates have been largely conservative, i.e., "safe" from the risk of over-escalation.

U.S. ESCOs generally do not guarantee all of their estimated savings, as a way to hedge against any project performance issues or errors related to savings estimation. For instance, ESCOs working with the federal government under DOE's umbrella ESPC contract on average guaranteed 92% of the estimated cost savings in their projects (Slattery 2018). Similar to escalation rates, setting this guarantee at an optimal level can be challenging. If this guarantee percentage is set too low, then both the guaranteed savings and the necessary payments to support those savings would be under-estimated. Lower payments would result in a longer contract term and in turn would incur higher debt service—and a lower NPV. On the other hand, setting this guarantee too aggressively can lead to a project that under-performs against the guaranteed level, thereby increasing the probability of a monetary shortfall that would have to be made up by the ESCO.

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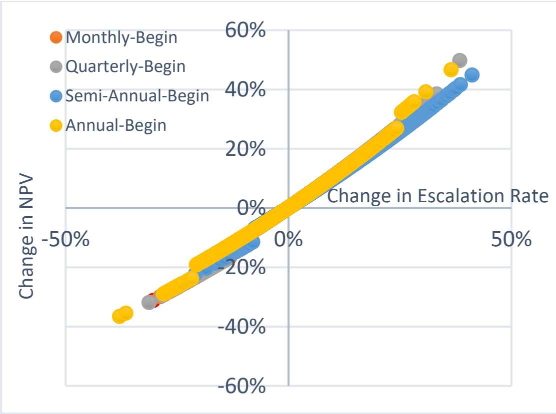

Figure 3: NPV as a function of escalation rate

Figure 4 shows the impact of guarantee percentage on NPV for different payment options. As the guarantee percentage increases, the NPV for a guaranteed savings project increases. It follows that it is financially prudent to use a higher guarantee percentage for ESPCs if the ESCOs are confident that they will be able to meet that level of performance. It should be noted that this guarantee percentage can be adjusted to account for the ESCO's risk tolerance, which is often based on the type of measures, complexity of the retrofit, and other factors.

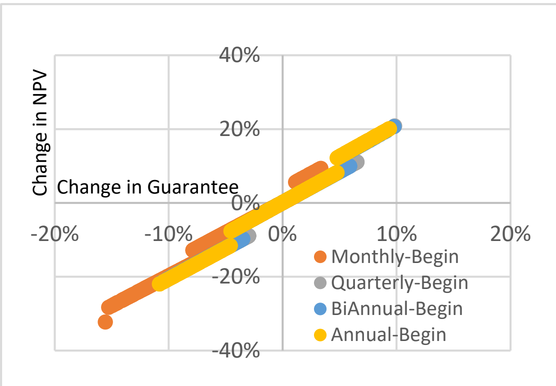

Figure 4: NPV as a function of percent of estimated savings that are guaranteed by the ESCO.

CONCLUSION

ESPC can provide an attractive, alternative financing mechanism in order to implement energy efficiency projects in India. These types of projects help customers reduce their energy consumption and associated costs with no up-front capital while containing some of the performance risks associated with the measures and project. However, there are many barriers that ESPCs face in India, including lack of credibility of ESCOs and the guaranteed savings model, lack of transparency and standardization among projects, and a general lack of the underlying data that documents the performance of these projects that can be used to value these projects for the lenders. This paper discusses eProject Builder, a web-based system that ESCOs and their customers can use to help develop and archive ESPC projects, as well as to track their performance throughout the project's performance period—and beyond. This tool also provides a transparent and standardized methodology to develop the amortization calculations to determine project financials, including payment schedules. It can be used to run financial scenarios based on various combinations of inputs to understand the cash flow implications of different project configurations. Also, ePB allows customers to compare proposed projects against benchmarks. The consistent and comprehensive collection of ESCO project data has important implications for the study of industry trends and best practices. Lessons learned from ESPC model in the United States are codified in tools such as ePB that may be useful to planners and policymakers in other countries like India where the ESCO industry is less mature. This tool provides a good framework for documenting and archiving aspects of ESPC projects, however some of the details may have to be customized and adapted to the Indian context to ensure that this tool aligns with the program requirements in India.

ACKNOWLEDGEMENT

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THE END OF DUMB HVAC ASSETS

Ananthapadmanabhan GS[1], Saksham Goel[2], Saksham Dutta[3]

[1]*Analytics &Automation Team*
Smart Joules Pvt. Ltd.
New Delhi, India
ananthapadmanabhan@smartjoules.in

[2]*Analytics & Automation Team*
Smart Joules Pvt. Ltd.
New Delhi, India
sakshamgoel@smartjoules.in

[3]*Product Development Team*
Smart Joules Pvt. Ltd.
New Delhi, India
Saksham.dutta@smartjoules.in

ABSTRACT

In a market where competition is a driving factor, organisations need to use technology to reduce operational cost, improve profitability, and improve their competitive edge. The coming years are expected to witness a shift away from dumb to "smart equipment", where data enables diagnostics to determine issues that may arise in future, and equipment self-report maintenance needs and automatically adjust operating parameters to function at their highest possible efficiency levels.

Previously, the manufacturer's knowledge of a product stopped once it left the factory. But now, via the feedback made possible through IoT, you can start to learn the usage and performance of these products in real world applications and make engineering changes to improve their reliability and efficiency.

In this paper, we present a recent case study of making a dumb AHU smart, including an analysis of costs and benefits associated with this transition. While people generally have the notion of better technology coming in with a hefty price tag, the case study shall explain how, at a comparatively nominal cost, a "dumb" AHU can be converted into a "smart" AHU. Moreover, with the operational and maintenance optimizations that are made possible with "smart" AHUs, shall make it a cost-effective investment, leading to un-interrupted efficient cooling, at the same time saving on energy consumption via operational optimization.

Through this case study, we also outline a vision of how IoT startups in India can usher this transition in the HVAC industry by entering into symbiotic partnerships with established OEMs.

Keywords— smart equipment, highest possible efficiency levels, established OEMs

INTRODUCTION

The HVAC system of a building comprises of various components, such as the chiller, chilled water pumps, condenser water pumps, cooling tower and air handling units. Traditionally, all these components are designed to run in fixed (constant) operating conditions, which may or may not be the optimum operating points throughout the year, month or even throughout the day[1]. For example, a chilled water pump may be required to pump 'x' GPM of water in the chilled water circuit of the system in the day but at night, due to less tonnage required only 'y' GPM of water may be required to be pumped. Such a scenario results in sheer energy wastage through multiple parts of the system. In the above scenario, we might be wasting energy through the chiller (by cooling extra water) and the chilled water pump (by pumping extra water). Such scenarios can be avoided by upgrading a system with **dumb HVAC assets to smart HVAC assets.**

Another perspective to switching from traditional manually operated HVAC assets to smart HVAC assets can be given in terms of maintenance. While traditional HVAC assets are known to straightaway breakdown, smart assets are capable to detect faults before they occur with the help of various sensors (such as temperature, humidity, pressure etc) installed and give user an alert before breakdown. This in turn helps us to service it before the whole system breaks down, hence lowering the maintenance costs as well as reducing the turn-around time (service interruption) of the issue.

Air Handling Unit

An air handling unit forms an essential part of a heating ventilation and air conditioning system. It plays an instrumental role in the whole system where it facilitates the heat transfer between the chilled water being supplied by the chiller plant with the air that is supposed to be cooled down.

Based on the amount of air being supplied to the supply area, an AHU can be categorized as:

- Constant air volume system
- Variable air volume system.

A constant air volume system can be considered as a "stock" AHU, which runs as per its design specifications through-out its life. A variable air volume AHU on the other hand is deployed with a variable frequency drive at the blower fan, as well as two-way motorized actuator valves on the AHU's chilled water line as well. The VFD present on the blower fan enables the operator to tweak the amount of air flow being supplied to the supply region(rooms) by changing the frequency of the voltage being supplied to the blower fan. If we reduce the airflow of the fan via the action on VFD the power consumption of the AHU is reduced. The above air handling units can be also categorized as "dumb" air handling units, with regard to the dependency they have on an operator for optimized operation, i.e., for changing the frequency of VFD for optimized performance or the position of the two-way valve on the chilled water line [2]. The same is also done at times, on the basis of a PID controller, based on area temperature as an observable.

In an AHU, the two-way valve can be considered as the primary accelerator for controlling area temperature as the volume of water passed to the AHU is directly proportional to the cooling delivered to the room. VFD allows the passage of air to the connected rooms, so it is the secondary accelerator in delivering cooling. It can be inferred that the two-way valve has more capability in bringing a significant change in area temperature in comparison to VFD in most of the cases. Depending upon the heat load, a two-way valve can be modulated between 0% open position to 100% open position, whereas a VFD can be modulated to give a power output ranging from 25 Hz to 50 Hz.

IoT and Smart Air Handling Unit

For converting a conventional asset to a "smart" one, Smart Joules has developed a **Building Management System (BMS), DeJoule,** which is an IoT based continuous energy optimization platform for bringing energy efficiency. It collects data from various sensors, VFD and motorized actuator valves, through an in-house developed controller and then processes this data for an HVAC site, allowing the user to monitor and control energy consumption of various HVAC assets.

User control on DeJoule can be exercised via three modes of operation – Joule Track, Joule Recipe and Thermostat. While Joule Track is a user interface which enables users to exercise semi-automated control of assets and Joule Recipe allows complete automated control of assets. The last mode of operation is the Thermostat mode which constantly modulates the control devices in a smart AHU based on the area temperature. It optimises comfort of the supply region and the energy consumption of the AHU. This software-based Thermostat algorithm has been designed, developed, tested and deployed across multiple air handling units in different HVAC sites across India.

Software Thermostat

The software thermostat is one discrete component of DeJoule which maintains thermal comfort in the region on the basis of the desired user temperature setpoint in the region. It is an algorithm based on the PID controller with special functionalities which brings extra energy savings, robustness and thermal comfort. On basis of the error generated between the desired setpoint and area temperature(observable), it gives corrective action on two-way valve and variable frequency drive (control parameters). The thermostat algorithm is executed inside the IoT controller and is activated whenever the setpoint is given by the user.

Predictive Maintenance

Lack of proper maintenance of a building HVAC system can lead to the development of faults in a system, which may be design related or equipment and controller failure related. These faults often result in energy wastage and if persistent over a period of time it may result in equipment breakdown leading to losses via equipment downtime, loss of indoor environment quality and the high cost of repairs which may have been avoided if the fault was caught at the right moment [3].

With IoT and Smart AHUs we can resolve this problem by studying the data from various temperature sensors installed in the air handling unit, based on which one can undertake preventive maintenance activities, thus avoiding "equipment breakdown". This in turn helps us to maximize the time an equipment runs in the most efficient condition, while minimizing our maintenance costs.

METHODOLOGY

Description of the HVAC system

The smart air handling unit considered in this case study provides cooling to the Out Patient Department of a hospital in Delhi. The area consists of a huge waiting area.

The air handling unit present in the region is a 25 TR AHU, fitted with a 5.5 kW motor and is designed to deliver 10,000 CFM of air. Since the HVAC system of the building was an old and inefficient one, the AHU for this particular region was replaced by a much efficient AHU in 2017. The AHU has also been deployed with a 5.5 kW Fuji Frenic Ace VFD and a two-way valve motorized actuator valve from Honeywell.

Some of the data points available for this AHU are:

- Power consumption of the VFD
- Two-way valve motorized actuator position
- Supply air temperature
- Chilled water inlet and outlet temperatures
- Area temperature

In this study, we shall make use of the above parameters for smart control as well as for preventive maintenance of the air handling unit.

Data acquisition and processing

For our case study, data was acquired from the air handling unit with a time interval of 1 minute since the beginning of this project through our IoT infrastructure. The data was collected in real time from various assets deployed at the AHU by the IoT controllers via communication protocols for example MODBUS communication etc. The data was filtered and was uploaded to DeJoule.

The data was then monitored and analysed, for deploying optimization techniques such as Joule Recipes or software-based Thermostat to minimize energy wastage while at the same time maintain indoor environment quality in the supply region.

As a backup these controllers also have the provision for storing the equipment data, in a case of emergency where the controller is not able to communicate with our user interface due to internet unavailability. This data is further transmitted online once the internet connectivity is regained, thus increasing its reliability.

In this paper, we shall put forth a cost benefit analysis which will compare the worth of smart AHUs with traditional AHUs. This will be done by analyzing the features and pricing as well as the energy consumption of both the AHUs under similar operating conditions. It will help us understand the feasibility of converting dumb AHUs to smart AHUs and utilizing features such as the software-based thermostat to conserve energy as well as help us maintain the AHU's at their optimum condition.

DUMB AHU vs SMART AHU

With the transition of a dumb AHU to a smart AHU comes various added opportunities to optimize and save on energy consumption of an AHU, such as:

Features	Dumb AHU	Smart AHU
AHU Remote Access	No	Yes
AHU Remote Monitoring	No	Yes
User Alerts	No	Yes
Thermostat	Yes (if installed)	Yes
Area Temperature	No	Yes
Observation based intelligent actions	No	Yes
Supply Air Temperature	No	Yes
Chilled Water inlet temperature	No	Yes
Chilled water outlet temperature	No	Yes

Table 1: Dumb Vs Smart AHU

In this case study we shall study about the benefits of software-based thermostat and the preventive maintenance approach that can be made use of to eliminate energy wastage while maintaining comfort.

SOFTWARE BASED THERMOSTAT

As discussed in the introduction, it is based on the PID controller. The acronym PID stands for Proportional, Integral and Derivative control. The P, I and D are terms in a control algorithm, and each has a special purpose. Initially, the error is computed by desired setpoint and measured area temperature from the

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room. The proportional term calculates the present error, the term integral is a summation of the past errors accumulation and the term derivative shows the future error by considering the rate of changes of the process [4]. Sometimes certain of the terms are left out because they are not needed in the control design. Thus, it is possible to have a PI, PD or just a P control. **Figure 1** shows the working of a conventional PID controller.

The PID controllers have three modes:

1. Proportional Control
2. Integral Control
3. Derivative Control

$$F(s) = Kp\, e(t) + Ki \int e(t)\, dt + kd\, (de(t) / dt) \quad (1)$$

F(s) is the output that is given to the AHU which in our case is two-way valve and VFD. PID controller is used widely in almost 85 percent of the control applications, but we have added functionalities that makes it intelligent, robust and energy efficient than a conventional PID controller [5].

emergency position configured for the tested AHU in this paper for VFD is 40 Hz and two-way valve is 75 percent) to not compromise comfort.

AHU PREDICTIVE MAINTENANCE

If we look at the data supplied by the various sensors deployed in a smart AHU, we can deduce some conditional parameters, which if not being followed by future data, can indicate about the health of the AHU, such as:

- If the difference between the chilled water in and chilled water out follows the historic trend but the supply air temperature is less than that indicated by the historical trend, it can indicate that although the heat transfer is taking place the amount of air to be cooled is less due to the air filters being choked. In such a scenario, although we are supplying the conditioned air at a temperature less than required, we are also sending in less air, which might not be able to cater to the requirements of the supply region.

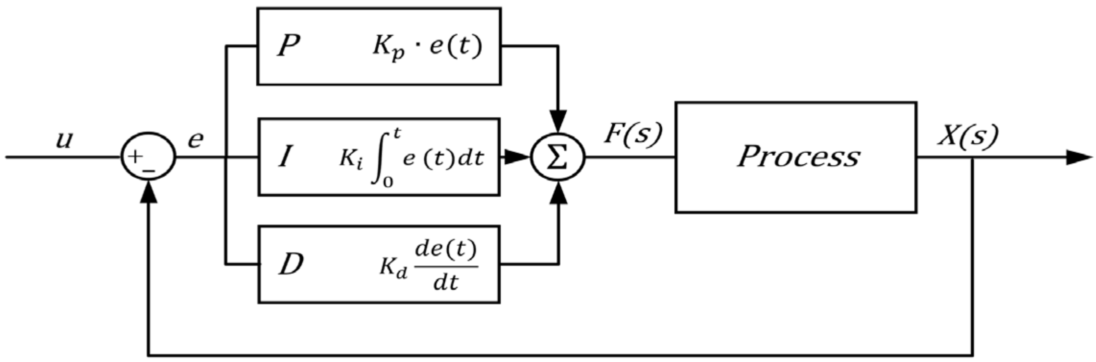

Figure 1: Block Diagram of a PID Controller

Benefits of Software Thermostat

PID controller is only triggered when there is a requirement of cooling or heating. If the temperature is already maintained, all the control positions are sent to the **minimum position (**The minimum position configured for the tested AHU in this paper for VFD is 30 Hz and two-way valve is 10 percent). This strategy gives extra savings during the operational hours of the AHU without affecting comfort. When the AHU is turned off, the VFD is automatically turned off and the valve is sent to its minimum position by the algorithm. In addition to this, if the temperature sensor and AHU status(ON/OFF) is not present to the algorithm due to network failure etc the control parameters are sent to their **emergency positions(**The

- If the difference between the chilled water inlet and outlet is really low, then it can be interpreted that no heat transfer is taking place. This can also insinuate that there might be scale formation on the chilled water coils inside the AHU, due to which heat transfer is taking place adequately.

The above two situations are critical to maintain occupant comfort in the supply region. If detected in time, it can help us maintain our equipment health, thus avoiding breakdown maintenance.

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COSTS ANALYSIS

For this case study we have also conducted an analysis for the initial investment required to procure the different types of air handling units discussed in the above section.

Assets	**Cost of CAV AHU** (USD)	**Cost of VAV AHU** (USD)	**Cost of Smart AHU** (USD)
25 TR AHU with 5.5 kW motor	4,184/-	4,184/-	4,184/-
5.5 kW Fuji VFD	---------	265/-	265/-
Motorized two-way actuator valve	---------	168/-	168/-
3x Immersion type temperature sensors	---------	---------	34/-
Area Temperature Sensor	---------	---------	35/-
IoT Controller	---------	---------	140/-
Panel	---------	---------	258/-
Total Cost	**4,184/-**	**4,617/-**	**5,517/-**

Table 2: Cost comparison of CAV, VAV and Smart AHU

Table 2 depicts the cost of various assets required to convert a "dumb" AHU into a "smart" AHU. While a constant air volume AHU differs from a variable air volume AHU in terms of a VFD and a two-way valve actuator, a smart AHU requires specific assets to be deployed for gathering data and processing it through IoT. For measuring area temperature and relative humidity Smart Joules have developed an IoT based sensor which transmits data from the rooms. A Joule IO controller is used for transmitting the data gathered from the sensors, online to a cloud data storage. An added cost is the cost of the panels which are required to protect the controllers from any physical damage. As we can gather from the above table, a smart AHU shall cost 900 USD more in comparison to a CAV AHU and 466 USD when compared to a VAV AHU.

The prices mentioned above are as per modifications done by Smart Joules. There are other OEMs in the market as well who manufacture smart AHUs. These smart AHUs can also be connected to our Building Management System DeJoule, for further optimization by deploying energy saving algorithms like Joule Recipe and software-based Thermostat.

To conduct a cost benefit analysis, we deployed a smart AHU with software-based thermostat to optimize its operational performance while at the same time maintaining occupant comfort levels throughout its operational period. The results of the same are shown in the sections ahead.

ELECTRICAL CONSUMPTION ANALYSIS

The software-based thermostat was tested in multiple regions. For comparing and calculating the savings, a sample period of 1 week (19^{th} July to 26^{th} July) was taken. Both 2019 and 2018 electrical consumption data were compared to calculate the savings generated out of the air handling units. Thermostat was active in the current period of 2019 whereas last year 2018 it was in manual mode. Last year energy consumption in kWh of the Air Handling Unit was taken as a baseline with respect to which this year's consumption was compared to calculate savings. In this case study, we shall study the results for the Private OPD AHU. **Figure 2** outlines two-way valve position, VFD output frequency, AHU status (On/Off) and average apparent power. In 2018, while the AHU was under manual operation, it consumed about **396 kWh**. In 2019, under thermostat mode, the setpoint that was given to the algorithm was 24.5° C, and the electrical consumption came out to be **243.56 kWh**, as shown in **Figure 2**. The decrease in consumption is **39 percent** relative to the manual mode of operation.

CHILLED WATER PUMP OPTIMIZATION

Custom logic was configured through Joule Recipe which had two-way valve positions as observable and the frequency of the chilled water pump was controlled. When the AHU's are turned off the two-way valves also attain their minimum position, i.e., 10% open position. Now the flow in the chilled water can be reduced by reducing pump VFD frequency for achieving savings from pumping cost. Joule Recipes were deployed to monitor the actuator valve position and according to number of valves closed, chilled water pump frequency was also reduced.

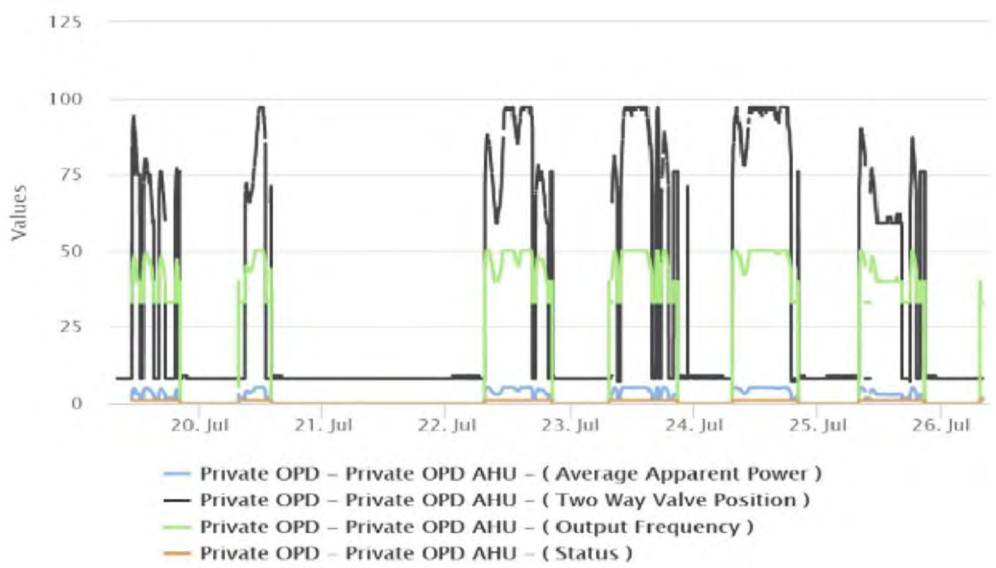


Figure 2: Parameters of AHU in Thermostat Mode

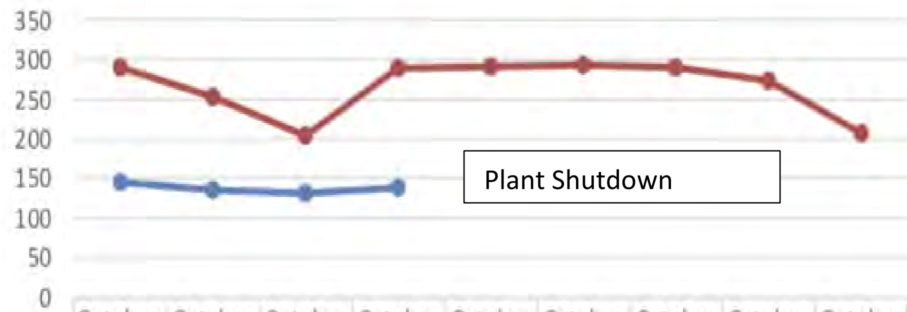
ELECTRICAL CONSUMPTION ANALYSIS

The energy consumption analysis of the chilled water pump after the thermostat-based Joule Recipe frequency optimisation was deployed. The frequency of the VFD of the chilled water pump was modulated using Joule Recipe and thermostat. Daily savings from this particular optimisation is 140-150 kWh/day for the chilled water pump as shown in **Figure 3.**

COST EFFECTIVENESS

For converting a manually operated AHU to a smart one, the cost of investment was 900 USD from **Table 2** in comparison to constant air volume AHU and from VAV AHU it was 466 USD. The air handling unit observed in this case study operates for 12 hours, for 5 days of the week (Monday to Friday) and for only 6 hours on Saturdays. The area remains closed on Sundays. From above, we may recall that the consumption of the AHU in 2018, for the same run hours was 396.76 kWh. After the deployment of software-based thermostat on the AHU, the electrical consumption of the AHU for the same time period in 2019 was 243.56 kWh. Thus, we generated electrical savings of 153.17 kWh amounting to 39% electrical consumption savings.

From the above data, we can calculate the average electrical consumption of the manually operated AHU



	October 19th	October 20th	October 21st	October 22nd	October 23rd	October 24th	October 25th	October 26th	October 27th
Consumption for 2019	145	135	131	138					
Consumption for 2018	290	253	204	289	291	293	290	273	207

Figure 2: Consumption analysis of chilled water pump

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per day which is 56.68 kWh (as per 2018 data). For 365 days, the consumption can be assumed to be 20,688 kWh. From electrical consumption analysis of AHU, software-based thermostat saves 39% energy consumption. Thus, energy saved can be estimated as 8,068 kWh.

Assuming the commercial electricity rate of New Delhi as 0.13 USD per unit for a year,

Total Monetary energy savings = 1,048 USD.

From the monetary energy savings, we can recover the cost in approximately 6 months for converting a VAV AHU to a smart one and one year for a CAV AHU.

Extrapolating the above data, we can assume that over the course of 10 years, one can generate around 10,014 USD of savings from a smart AHU, when compared to a CAV AHU. This is calculated assuming that no sensor replacement is required and the maintenance of mechanical parts shall be the same in both the AHUs.

DISCUSSION

In this paper we have presented a case study regarding the conversion of a dumb AHU into a smart AHU and how with the help of IoT we can optimize the performance of the air handling unit remotely using our building management system, DeJoule. While there are other OEMs in the industry who manufacture smart AHUs, these AHUs still have to be controlled via a control panel present on the AHU. Manufacturers such as Stulz, Koja OY, Advantek etc manufacture smart AHUs which have features such as temperature control, humidity sensors, automatic fresh air compensation etc. They also have an inbuilt alert system for informing the user about any pressure, temperature abnormalities in the AHU. Although these assets have MODBUS connectivity, they are still not connected to a single building management system, via which we can monitor and optimize our whole HVAC system continuously and remotely [6]. With the help of smart AHUs we can optimize individual AHU units and utilising the BMS efficiently we can optimize any asset of a HVAC plant.

From the paper, it is evident that if we don't convert the asset to a smart one, we will be wasting energy due to manual operational inefficiencies. In addition to this, there will be no alerts for unknown system behaviour, making us rely on only regular manual inspection of equipment for predictive maintenance of thee equipment. Qualitatively, converting the asset to a smart one will ensure timely maintenance, minimum system failure, automation of commands on the control parameters (dampers, valves, VFD etc), optimum manpower and energy consumption. Quantitatively, the equipment shall be operating 35-40 percent more efficiently with respect to manual mode of operation, with less maintenance cost.

CONCLUSION

HVAC operated buildings consume 40 percent of India's electricity consumption and is heavy on the pockets of building owners due to high electricity bills. If we scale the solution presented in this case study of converting the ineffective assets to smart ones nationwide in all major consuming HVAC operated facilities, we can save huge amount on consumption and the saved electricity can be directed towards energy deficit areas. Within a period of eight to ten years, the whole ecosystem shall profit from usage of such smart assets.

The electricity DISCOMS will essentially gain from buildings equipped with intelligence and can use their data to improve decision making and avoid massive electricity breakdowns. If we start using smart assets nationwide, we can solve the energy crisis in India to a great extent. Ultimately, this will aid the Indian Cooling Action Plan in achieving its goals of reducing cooling demand, refrigerant demand and cooling energy requirements. Our organisation, Smart Joules, an energy saving company (ESCO), is actively involved in designing, testing, developing and deploying new optimization techniques, based on the data recorded from such smart assets. The testing of these solutions done in multiple facilities across India, accounting for the different climatic conditions present. We do it by monitoring the equipment data through IoT controllers. Monitoring the assets helps us in timely maintenance of site assets, retrofitting inefficient equipment, testing custom designed techniques, algorithms and machine learning to minimise energy wastage.

With the help of Smart AHUs the management facility of cooling systems across various countries like India can benefit from real time tracking of accurate data from HVAC enabled facilities, maintain ambient cooling in the building and optimise consumption respectively. The assets in the facilities are powered by artificial intelligence to take decisions on their own and act accordingly.

NOMENCLATURE

Constant Air Volume AHU (CAV AHU) - A CAV AHU delivers a constant flow rate of air to the supply area, while the supply air temperature is varied to maintain area temperature.

Variable Air Volume AHU (VAV AHU) - A VAV AHU delivers a variable flow rate of air, depending upon the supply area requirement, by changing the frequency of the VFD on blower fan.

Building Management System - A building management system comprises of various control assets, IoT controllers and an online ecosphere, through which a user can monitor and control equipment behavior on a real time basis.

Two-way valve - A control valve fixed on the chilled water outlet line to regulate the flow of chilled water in the chilled water inlet of the AHU. This may be physically controlled, or motorized, for automation.

Variable Frequency Drive - A VFD is a motor controller that drives a motor by varying the frequency and in effect the voltage being supplied to the motor, in effect changing its output as per requirement.

Observable Parameters - It is defined as the parameters required for the control logic to observe and take command on the control parameters. It can be a function of values from multiple sensors, a value from a single sensor etc.

Control Parameters - It is defined as the parameters required for the control logic to execute actions on so that the observable parameters achieve the desired setpoint.

Emergency Position - It is defined as the position for control parameters when the observables stop coming to the control logic. The emergency positions for the control parameters trigger when the observables stop coming to the control logic.

Minimum Position - The positions for the control parameters when there is no need for modulation as the observable has attained the setpoint, so the control parameters are sent to their minimum positions to optimise energy.

ACKNOWLEDGEMENT

This research paper is the result of efforts made by many people apart from the authors. Mr. Arjun P. Gupta, Founder & CEO, Smart Joules Pvt. Ltd. and Mr. Ujjal Majumdar, Director & COO, Smart Joules Pvt. Ltd. have played a major role in shaping this research and guiding us through hurdles faced. From the technical team, Mr. Dishant Arora & Mr. Rahul Raj have helped in improving the functionality of software-based thermostat for more optimized performance while Smart Joule's field engineering team have played a crucial role, being on stand-by to avoid any trouble that may be caused. It feels immense pleasure to express our gratitude to all of the above for helping us in our research.

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ACHIEVING BUSINESS COMPETITIVENESS THROUGH SMART THERMOSTATS FOR HOTELS

Soorianan Narsiah,

Energy Efficiency Programs
Summerhill Group
Toronto, Canada
snarsiah@summerhill.com

ABSTRACT

Amidst fierce competition in the hotel industry, along with an average operating margin of 5%, hoteliers must carefully manage their operating costs in order to stay profitable and successful. Financial success is typically measured as RevPAR (average revenue per available room) but nowadays there is also a serious endeavour towards becoming green certified such as LEED. Since they are heavy on fixed and tangible assets, hotels require a high amount of working capital to meet a lot of short-term financial obligations among which utility costs represent approximately 6%[1]. Thus, any opportunity to reduce energy costs should be welcomed.

This paper presents a case study to analyse electricity savings by implementation of temperature setback control strategy on room HVAC units at a Best Western hotel in Canada's capital city, Ottawa. Temperature setback control allows the original setpoint to drift lower (heating mode) or higher (cooling mode) when the guest is out of the room. Consequently, the heating or air conditioning unit doesn't have to run during the occupant's absence leading to a reduction in energy consumption.

During the study, samples of programmable thermostats were installed in 10 similar rooms which are also facing the same side, where half were on energy saving mode programmed with setback control while the other half were on regular operating mode. Analysis of data collected for 8 weeks at 5 mins intervals suggest an average savings of 30% between setback and regular modes which translates into 13% of total electricity savings for the hotel.

Keywords—setback control, hotels, energy efficiency, HVAC, programmable thermostats, climate change *(keywords)*

INTRODUCTION

Best Western Plus Ottawa is one of the upper-midscale of the Best Western brand. The property located at 1274 Carling Avenue is conveniently positioned in the central part of Ottawa City and serves both customers who are travelling for leisure or business. The hotel provides 121 guest rooms, a restaurant and concierge services, meeting rooms, recreational amenities such as a fitness centre and a pool.

From an energy consumption point of view, the hotel consumes an average of 1,000,000 kWh of electricity annually at a total cost of CAD 150,000. The main electrical loads are lighting and HVAC. Climate in Ottawa, (and Canada in general) varies from extreme cold (-30ºC) to very hot (+ 35ºC) across the four seasons. Thus, the building requires as much heating in fall and winter as much as it need cooling in spring and summer. During a few weeks in spring and fall time a typical "balance period" is observed, where cooling and heating requirements are at their minimum, even zero on some days.

Heating is provided by electric baseboard heaters (rated at 2,000W on average) while cooling is provided by window airconditioning units rated at an average of 9,000 Btu/hr.

PILOT TESTING

Samples of the proposed programmable thermostats were installed in 10 rooms and paired so that one room was set on energy saving mode (EMS "ON") and the

[1] https://www.energystar.gov/sites/default/files/buildings/tools/SPP%20Sales%20Flyer%20for%20Hospitality%20and%20Hotels.pdf

other on regular control (EMS “OFF”). Note that the room pairs were selected so that they are of the same dimensions, contain the same furniture and appliances, and most importantly facing the same side, so that they receive the same amount of solar energy. The pairs are listed in Table 1 below:

Table 1: Test thermostats pairs

Pair #	EMS ON	EMS OFF
1	311	321
2	315	317
3	305	309
4	316	312
5	308	310

Equipment runtime and % occupancy are recorded by the thermostats at 5 minutes intervals. Figure 1 below demonstrates a typical display.

Figure 1: Display from thermostat control

Note that the % occupancy mentioned here refers to the time when someone was in the room. It does not necessarily reflect the actual % of rooms sold and thus must not be confused with it.

The experimental period was from 4th of November 2017 to 10th of January 2018. Thus the data collected were essentially during winter where the baseboard heaters were running. Although the following results presented below are for heating, the concept does apply to the cooling season as well.

Data were downloaded in excel format and analysed. Equipment runtime were converted to daily kWh (runtime x kW draw from baseboard heaters which was spot measured) and the 5min interval percentage occupancy were averaged for the day. Thus we have a comparison of daily kWh consumption v/s daily average occupancy as well as the average temperature setpoint, demonstrated by Table 2 below.

Table 2: Setpoint & kWh v/s high occupancy

Date	Average Temp. setpoint °C	Total kWh	% occupancy
04-Nov	22.05	29.77	81.7%
05-Nov	21.78	18.16	47.2%
06-Nov	21.50	5.93	5.0%
07-Nov	21.73	6.46	29.1%
08-Nov	22.51	6.63	72.5%
09-Nov	22.49	11.88	62.8%
10-Nov	22.43	13.02	77.8%
11-Nov	21.40	9.45	74.3%
12-Nov	21.52	15.55	74.5%
13-Nov	21.52	8.36	50.4%
14-Nov	21.76	8.06	25.2%
15-Nov	22.45	9.42	100.0%

DATA ANALYSIS

The objective of the experiment is to compare the energy consumption between EMS “ON” & “OFF” modes while also monitoring occupancy levels. Figure 2 represents the data collecetd from Room # 311 which was on “EMS ON” mode. The chart displays how the daily kWh follows the reduction of occupancy level. This means that the thermostat automatically lowers the original setpoint while the guest was away.

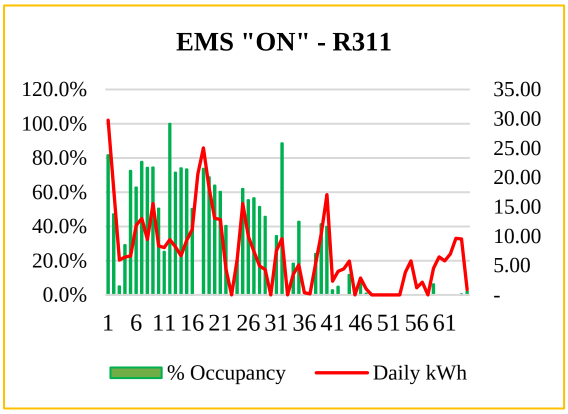

Figure 2: EMS “ON – Compare occupancy v/s kWh

Figure 3 below is a zoom in to display a close up of the changes from Day 18 to 31 where the decline in kWh with % occupancy is clearly visible.

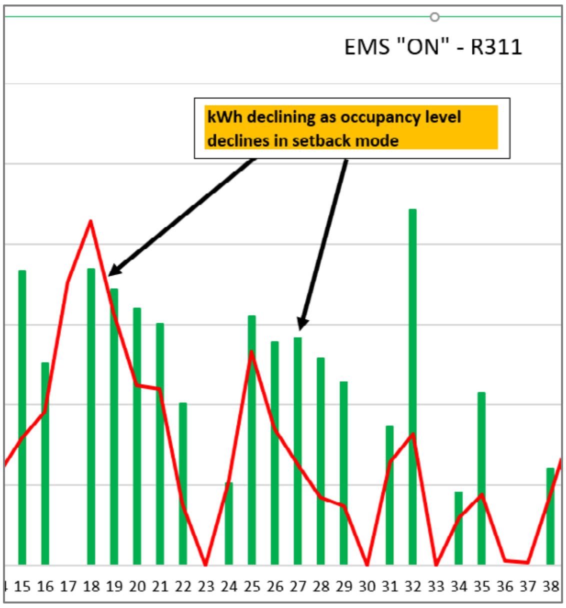

Figure 3: Days 18 to 31 Comparison occupancy v/s kWh

Figure 4, on the other hand, displays the variation of daily electricity consumption (kWh) compared to daily average occupancy percentage for Room # 321 which is the one on “EMS OFF” mode in the first pair. The high electricity consumption during periods of low or even zero occupancy from days 26 to 61, is quite noticeable. This means that the heating units kept on running to maintain the original setpoint even though there were no one in the room. The setpoint was probably set by the previous guest or the housekeeping team.

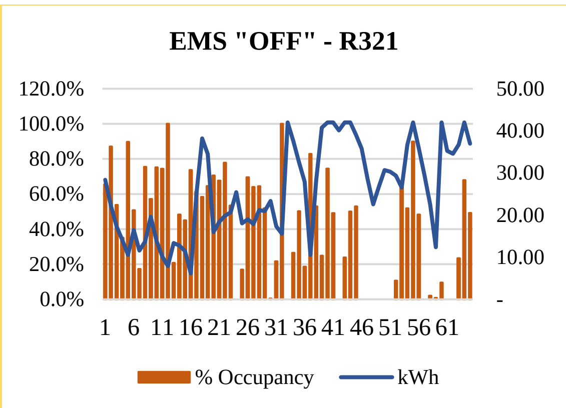

Figure 4: EMS “OFF – Compare occupancy v/s kWh

For this particular pair an average savings of 72.9% were calculated for the 65 days period under study. Tables 2 (above) & 3 (below) show some of the values of daily kWh compared to occupancy during the EMS “ON” mode which were plotted in Figures 2&3 above.

Table 3: Setpoint & kWh v/s low occupancy

Date	Average Temp. setpoint °C	Total kWh	% occupancy
17-Dec	18.96	2.33	2.8%
18-Dec	19.15	4.03	4.8%
19-Dec	18.75	4.43	0.0%
20-Dec	19.97	5.78	11.7%
21-Dec	20.05	-	0.0%
22-Dec	20.95	2.88	8.1%
23-Dec	20.60	1.02	0.8%
24-Dec	20.25	-	0.0%
25-Dec	19.58	-	0.0%
26-Dec	19.01	-	0.0%
27-Dec	19.79	-	0.0%
28-Dec	19.42	-	0.0%

Each of the five pairs were analysed in the same way and Table 4 below presents the overall savings results for the 65 test days. An average savings of 30.4% were achieved.

Table 4: Summary of savings

Pair #	EMS ON	EMS OFF	Electricity savings %
1	311	321	72.9%
2	315	317	46.2%
3	305	309	-11.8%
4	316	312	28.6%
5	308	310	16.2%
	Average Savings		**30.4%**

The negative savings noted within pair #3 demonstrates that there is also a potental risk of not achieveing savings. This could be possible in cases where guests have relatively higher setpoints (for heating) or relatively lower (for cooling) and they are also mostly occupying the rooms after checkin.

It is to be noted that the thermostats usually have a few options for the EMS “ON” modes. The one in this case study offered 5 options where option 5 was the most aggressive which means the setback is higher (approx 4-5 degrees) and option 1 least (1-1.5 degrees). The thermostat control usually learns the recovery time to come back to the original setpoint after setback, and adjusts its cycle accordongly. Thus, depending on the efficiency of the HVAC system, there are cases where option 5 maybe too aggressive and can impact guest comfort significantly because the system may take too long to recover. Such observations must be made during the pitot testing which will inform the overall setback level once the application is rolled out to all the rooms.

ELECTRICITY SAVINGS

The total electricity consumption of the hotel was 1,032,000 kWh in 2016. Based from a previous study the baseline for heating only was calculated at 422,255 kWh (41%), which is quite significant.

Applying 30.4% savings from thermostat setbacks to the heating mode suggests an energy savings of 126,676 kWh annually, which is evaluated at $ 19,128 (@ $0.151/kWh). This represents 12.7% of the total electricity bill of the whole facility.

Financial Analysis.

Table 9: Financial Matrix

Projected Annual Savings	**126,676**	kWh
Electricity Costs	$0.151	$/kWh
Projected Annual Cost Savings	$19,128	
Project Costs	$67,000	
Project payback	3.50	years
Additional Revenue per room	**158**	
increase in RevPAR	$0.722	
Total CO_2 avoided annually	89,560	kg CO_2
Equivalent of passenger vehicles off the road	9.40	

Electricity savings from setback control across all 121 rooms is expected to increase the RevPAR by $0.72 and save an equivalent of close to 90 metric tons of CO_2 annually which is the equivalent of displacing 9.4 cars off the road.

CONCLUSION

While this study was conducted during the heating season in a Canadian winter setup, the author is convinced that comparable results with regards to percentage savings are quite achievable during the cooling season as well. For a geographic location such as India, where cooling is most common it is expected that air conditioning load will occupy a significant percentage of the hotel's total electricity bill, which could be up to 50%. Thus it will be worthwhile conducting a pilot testing for any facility to assess the impact of setback controls on energy consumption. The results of this study also encourages hotel owners to adopt this practice towards their sustainability goals and endeavours to be green certified.

The 12.7% monetary savings may be diluted among the hotel total expenses in the accounting books, however, if we analyse the collective impact across all the 90 million hotel rooms (Statista, 2019) in India significant progress will be made towards climate change mitigation.

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A SYSTEMATIC METHODOLOGY FOR REDUCING COMPRESSOR CONSUMPTION IN MANUFACTURING INDUSTRY CLUSTER

Kajol[1], Mohtasib Mohammed[2]

[1]*Energy Program*
World Resources Institute India,
Bangalore, Karnataka, India
kajol@wri.org

[2]*Eco Energy Management System)*
Pune, India
info@ecoen.co.in
mohtasib@gmail.com

ABSTRACT

In a manufacturing industry such as Automobile component units, compressed air consumption accounts for 30%-40% of total consumption. Eventually, one of the most expensive utility in a manufacturing facility. In small and medium sized enterprises (SME) the awareness on cost effective energy efficiency improvement for compressor are neither priority nor they have detail know-how of different methods. This paper will describe the energy consumption pattern in manufacturing cluster in Aurangabad, compressed air usage, systematic method for adopting various energy-saving measures in compressed air system, such as optimising the pressure, VSD, arresting leakages, compressed air network inspection, recovering waste heat. The paper will use a general modelling technique to establish relationship between compressor power consumption and air output to estimate energy consumption, energy savings, cost savings, and payback period. The study is based on energy assessment study undertaken in 20 automobile component manufacturing industry in Aurangabad cluster. The amount of saving is extrapolated for energy efficiency demand aggregation at cluster level to estimate cluster energy saving and emission reduction

Keywords—Energy Efficiency, MSMEs, Industries, Air Compressors, Demand Aggregation *(keywords)*

INTRODUCTION

Manufacturing sector in India is highly diversified both in terms of manufacturing processes and geographic locations. Out of 63.3 Million micro, small and medium (MSME) scale, 19.6 Million units are manufacturing industries [1]. According to the NITI Aayog, India's energy and electricity demand is projected to grow at Compound annual growth rate of 3.7%-4.5% and 5.4%-5.7% respectively till 2047 [2]. This indicates, in future the demand of fuel and natural resources will rise. In an industry 57% of primary energy input is not converted into useful energy for production [3].

Transition to clean energy is essential to improve energy security of supply, environmental protection and economic growth. MSME industries are always stressed by energy consumption, low operational efficiency and high costs. Different studies underline the significant potential of improving energy efficiency in manufacturing industries; the saving potential varies from 10-40% of total input energy based on different measures [4] [5]. However, there are several barriers and challenges, MSMEs face in adoption of efficient methods [5] [6].

(a) relatively high investments for efficient technologies
(b) Lack of skilled manpower and time for energy efficiency measures
(c) Lack of organisational responsibility
(d) In-depth knowledge and understanding of energy efficiency measures
(e) Ability to take risk about new technological implementations

Our learning is based on walk through energy assessment study undertaken in 20 numbers of automobile component manufacturing SME units in Aurangabad cluster. This paper describes the energy consumption pattern in manufacturing cluster in Aurangabad, compressed air usage, systematic method for adopting various energy-saving measures in compressed air system and learnings from demand aggregation model developed for effective adoption of energy efficiency in compressed air system. The paper uses a general modelling technique to estimate energy consumption, energy and cost savings, and simple payback period. The saving is further extrapolated for developing demand aggregation business model at cluster level to estimate energy saving, monteray saving and emission reduction.

AUTOMOBILE CLUSTERS IN INDIA

The auto-components manufacturing cluster contributes to 2.3% of India's Gross Domestic Product (GDP) in 2017-18 [7]. There are three major automobile component manufacturing clusters in India, (a) Delhi-Gurgaon-Faridabad-Ghaziabad-Gautama Buddha Nagar, (b) Mumbai-Pune-Nasik-Aurangabad-Thane, and (c) Chennai-Bangalore-Dharmapuri-Vellore-Kanchipuram - Thiruvallore [8] [9].

We worked with Aurangabad based automobile cluster in West India. There are four industrial clusters in Aurangabad district. - Chikalthana Maharashtra Industrial Development Corporation (MIDC) Area; Shendra MIDC Area, Railway Station MIDC and Waluj MIDC Area. Out of the 4 clusters, we worked with Marathwada Association of Small-Scale Industries & Agriculture (MASSIA) located across 2 clusters: MIDC Chikalthana and MIDC Waluj.

Cluster Energy scenario and Compressor application

Three main factors play a significant role in assessing the level of energy consumption in an economy: (a) type and total production, (b) the composition or structure of the economy, (c) the output per unit of energy consumed [10]. On the basis of the willingness of MSME units to share the data, we approached 75 auto component industries with the support of MASSIA (Marathwada Association for Small Scale Industries). The data collected as a part of our project for developing GHG reduction roadmap for MSME clusters in India. Walkthrough audit was done in 20 units for collecting compressor specific data.

The main source of energy in Industries is electricity. The total connected load of units under scope of this study is 6.6 MW, with 15 MU consumption per year. 17% of industries (10 nos. out of 53 units) have less than 0.02 MUs of electricity consumption per year.

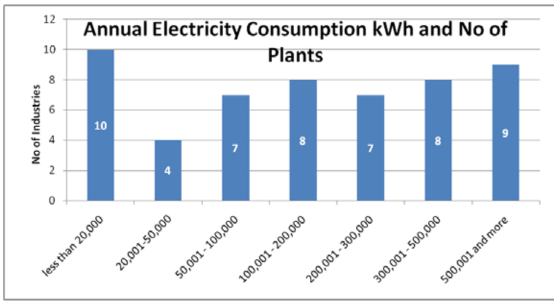

Fig No. 1: Range of Annual Electricity Consumption in SME Cluster

About 13% industries are using other sources of energy as fuel in the process. The fuels used in the process are LPG and furnace oil. As the power supply in Aurangabad cluster was fairly stable the usage of DG set and hence diesel consumption is limited.

Energy consumption of the unit also depends on number of operating hours. The units were classified based on the operating hours of the units. 56% of the plants are operated 24 hours where as 31% were with 16 hours. Only 13% of the surveyed plants were found to be operating only one shift. This is essential for calculating the annual saving.

SME engaged during the study in manufacturing of automobile components without heat treatment is depicted in the figure no. 2 below.

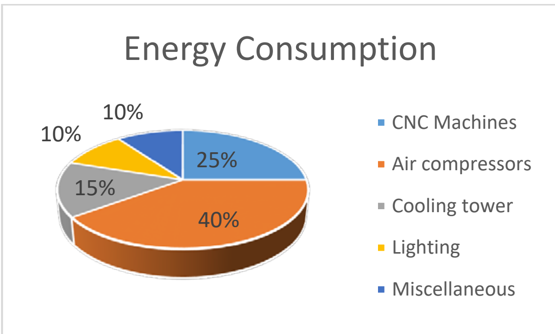

Fig No. 2: Energy Consumption in equipment across SME cluster

As seen from the graph, air compressors are main equipment and the energy guzzlers in manufacturing and engineering industries. In automobile manufacturing sector, air compressor account for 30%-40% of total consumption.The total compressor load in the cluster is in the range of 2 to 2.6 MW. Air compressor, converts electrical energy into mechanical energy (pressurized air). The pressurised air is stored in air receiver tanker, from there it is supplied for process requirements. The process requirements depend on the type of industries, and can be used for drying, cleaning, instrument air, pneumatic operations. At the end point 10-30% energy reaches for process, while the remaining energy is wasted into

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unusable heat energy such as friction, noise, operational misuse which is 70-90%.

During the walk-through study to 20 industries, key observations.
The projects identified were:

1. Arresting of leakages in compressed air distribution system

During the walkthrough survey, it was identified that leakage percentage in compressed air distribution system was in the range of 35% to 60%. This was a common scenario in most of the SME industries. Although all industries know that this is a loss to them, they do not have the manpower to arrest the leakages. As arresting leakages is not a onetime activity, the leakages need to be checked and arrested on a periodical basis. Identification and arresting of leakages had potential for demand aggregation. Few service providers / entrepreneurs can be developed to provide this service to a cluster/part of cluster. This will not only improve energy efficiency but also generate employment.

2. Optimizing compressed air generating pressure

The compressed air generating pressure was quite high as compared to required pressure. Optimizing generating pressure will be an energy efficiency project which can be implemented without any investment in most of the cases. Study of compressed air requirement and setting to optimized pressure can also be aggregated for the cluster.

3. Installation of VFD on the air compressor

In a screw compressor, load/unload in a common method for capacity control. Compressor is set to load and unload based on required pressure. During unload time when air compressor does not deliver any output, it still consumes around 30% of full load power. During the study, it was observed that there were cases where compressor originally had VFD, it was either bypassed or removed as technically qualified manpower was not available to service the VFD. Apart from this, there was lack of expertise in integrating VFD on existing air compressor. Installation of VFD on the existing air compressor would be a good potential for demand aggregation provided that good technical expertise is available with the integrator.

4. Replacement of existing air compressor with energy efficiency air compressor

As most of the air compressor in the SME industries were up to 30kW rating, replacement of these air compressors with energy efficient air compressors with IE4 motors or Permanent Magnet Motor would deliver significant energy saving. On pilot basis when an air compressor of 30kW was replaced with an air compressor of 22kW (Permanent Magnet Motor and VFD) reduced energy consumption by around 20%. Simple payback for the project was around 14 months.

It is estimated that after demand aggregation, the air compressor cost will reduce by around 20% and payback will be in the range of 10-12 months.

This will be one of major demand aggregation potential project. Under this, replication potential will be highest along with reduction in energy consumption.

5. Basic automation to stop idle working of equipment during non-working hours

Another identified energy saving potential in the cluster was basic automation to stop idle working of equipment like cooling tower, air compressor etc during lunch break, shift change or tea breaks. Although major machines are switched off during the idle time, the equipment which are placed at some distance like cooling tower, air compressor or blowers keep working during non-working hours also. With simple timer logic or interlocks, operation of these equipment can be stopped during idle hours. In this energy saving measure replicability is not high, but a service provider can be developed to look in this aspect of demand aggregation.

6. Replacement of motors with IE3/IE4 motors
7. Motors are one of the major energy handling equipment in the industry. However, their replacement on demand aggregation basis needs more detailed study of the application. In the automobile cluster, where the project study was carried out, most of the motors were either with CNC machines, hydraulic power packs, press machines etc where motors are not loaded on continuous basis.

Based on the study and common energy saving opportunities, it is estimated that potential to reduce the energy demand for the industries under the scope was in the range of 1 to 1.3 MW. Annual energy saving potential for these industries would be in the range of 2 GWh to 3 GWh.

MODELLING THE RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND SAVING

During our study, we observed misconceptions about the operations and usage of compressed air: Common belief are:

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- Operating compressor at higher pressure means higher flow
- Compressor should be operated at rated operating pressure

An air compressor, output consists of flow (Q) in CFM (cubic feet per minute) and pressure (P) in bar. Input power or power consumption (W) is directly proportional to flow and pressure. Any change in pressure or flow will impact power consumption of the air compressor [11].

Relation in compressor pressure and Power:
In an air compressor, ambient air is drawn to increase its pressure. In the process of increasing the pressure, its temperature also increases. Work done by a compressor can be given by

$W = m\ cp\ (T2 - T1)$ …… Eq. 1

In the air compressor along with temperature, pressure is also increased.

For polytropic compression of an ideal gas:
$T2 = T1\ (P2/P1)^k$ …………… Eq.2

where P1 and P2 are the entering and exit pressures respectively, and k = 0.2857 for air. T1 and T2 are the initial and final temperature of air.

Thus, compressor work can be calculated as:
$W = m\ cp\ T1\ [(P2/P1)^k - 1]$ ……. Eq.3

Equation 3 shows the that power required by the air compressor is proportional to mass, inlet temperature and outlet pressure.

Actual power required for the compressed air will also depend on efficiency of motor and efficiency of air compressor.

$W = (mcpT1\left[\left(\frac{P2}{P1}\right)\right]^k - 1)/(\eta m\ x\ \eta_c)$ … Eq.4

Where η_m is efficiency of motor and η_c is efficiency of air compressor.

Estimating Energy Savings in Compressed Air Systems – A case demonstration.

In one industry a demonstration project was taken up to estimate the actual energy saving for further estimating the saving for cluster. Two interventions were taken up:

- Replace the air compressor with energy efficient air compressor.
- Reduce generating pressure by 0.3 bar.

The old inefficienct screw air compressor of 45kWwas replaced with energy efficient (EE) screw air compressor of 30kW with variable frequency drive (VFD). Also, keeping temperature and flow rate constant, the compressed air generating pressure is reduced from 7 bar to 6.7 bar (0.3 bar reduction).

Using equation 3, energy saving in the compressed air is estimated on percentage basis by using the variables of Mass flow rate (m), inlet pressure T1 and outlet pressure P2. The average energy consumption saving is estimated.

The average monthly energy consumption before replacement was calculated as 31,100 kWh, and post reduction the consumption was reduced to 24,400kWh, i.e about a reduction of around 21% in total energy consumption. Graph below shows change in energy consumption after replacement.

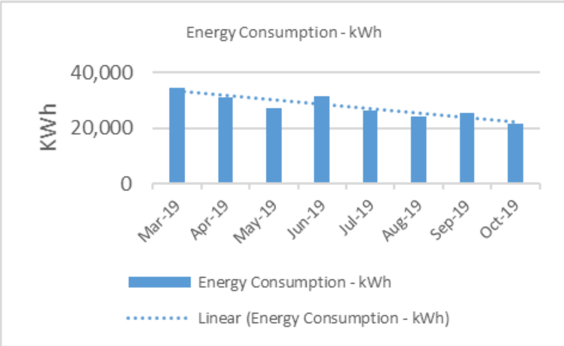

Fig No. 3: Energy Consumption reduction with replacing Old compressor with EE compressor

BUSINESS MODEL FOR IMPLEMENTATION AND SCALING OF ENERGY EFFICIENCY IN SME CLUSTER

Aggregating the compressor energy demand in Cluster

Demand aggregation is a progressive business model applicable not only for the products but also for the services. In both cases, the focus shifts from project based energy efficiency improvement to programmatic based energy efficiency.
In a particular MSME cluster, the type of connected load is identical to 50%-60% based on our experience. Operating and maintenance practices of the industries also remains largely same. Under these conditions, programmatic approach is energy and cost effective. Under programmatic based energy efficiency following activities were identified:

1. Common energy efficiency projects in the sector through data collections and field visits
2. Conducting workshops and awareness sessions for management/owners of the units.

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3. Creating demand of energy efficient technologies and services
4. Aggregating demand and implementation

Amongst all the identified opportunities mention above energy saving in compressed air system provides a good opportunity for demand aggregation. All industries have at least one air compressor in the facility. Projects with investment:

1. Installation of VFD on the air compressor
2. Replacing existing air compressor with optimum capacity air compressor
3. Basic automation to avoid idle running

Compressor contributes to around 30% of total electrical energy consumed by the plant. The total annual energy consumed in 53 units was 20,452 MWh. Considering 30% of the energy consumed is by air compressors, total electrical energy consumed by the air compressor would be 6136 MWh. Based on the walkthrough assessment and demonstration study, saving potential in the air compressor is estimated around 40% by improving energy efficiency with compressor upgradation and energy conservation by reducing leakages and avoiding idle running.

Table 1: GHG mitigation potential through air compressor efficiency

SNo	Head	Unit	Value
1.	Annual energy consumption for 53 entities	MWh	20,452
2.	Energy consumed by air compressor load	MW	6136
3.	Saving potential in air compressor	%	40
4.	Annual energy saving potential	MWh	2454
5.	Annual GHG reduction potential	tCO_{2eq}	2013

We estimate that the GHG emission reduction potential for the cluster of 912 industries would be 26,998 tCO_{2eq} and reduction in annual energy consumption would be around 33.1GWh.

This is equivalent to annual energy saving of 2400 MWh and reduction on CO_2 emissions by 1968 tCO_2/year. Progressive reduction in electricity consumption for SME cluster is depicted in figure no. 4

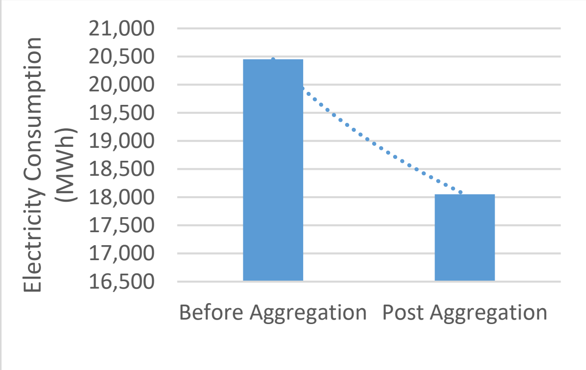

Fig No. 4: Processive reduction of electrical consumption with aggregation in compressor.

Energy efficiency in the compressed air system can be improved by adopting the aggregating model. Apart from the SMEs, the aggregation model would benefit:

1. Equipment Supplier:
   a. Supply of new energy efficient air compressor
   b. Supply and installation of VFD for the air compressor
2. Service Provider:
   a. Development of a service provider who would ensure that leakage percentage is maintained at minimum level.

In the process of aggregating the demand for programtic based energy efficiency of air compressors in cluster, key stakeholders were identified. The role of each stakeholder is explained below:

1. Industrial association:
   Industrial association is one of the most important stakeholders in the implementation of energy efficiency in the cluster. They can bring all industries under one roof and start the process. With involvement of industrial association, confidence of industries also increases.
2. Industries
   Industries are the final decision makers and implement the projects. Keeping the demand aggregation process transparent build trust in industries to participate actively in the entire process.
3. Technical Consultant
   Role of technical consultant is to collect actual site data, identify technically and financially feasible project, identification of suitable technology providers and contractor. The technical consultant also carry out

detailed study of each participating industry to analyse their requirement.

4. Technology Supplier: The suppliers for energy efficient technology and after service of equipment for MSME cluster is centre
5. Financial Institutions:
   Bringing financial institutions to the board assist the industries who would like to avail funding for implementation of energy efficiency projects.

With all stakeholders working together, the methodology adopted for demand aggregation of energy efficiency of compressor is daigramatically shown in figure 4.

Fig No. 5: Methodology for Demand aggregation in compressor for Eenrgy efficiency

With aggregated demand, the team of all stakeholders were in a much better position to negotiate the supply terms and condition with the suppliers. The advantages of this model is:

1. Active involvement of industrial association and industries where knowledge will be shared in depth with them
2. Unbiased selection and finalization of vendors as their all stakeholders will be involved in decision making process
3. Tailor made solution for each industry
4. Easy access to finance with different financial institutions
5. ESCO model for interested industries

Demand aggregation for renewable energy is implmeneted, which resulted in reduction of installation cost by around 35-40%. In the absence of this model, the payback would have been more than 4 years. With adoption of above business model, payback is close to 3 years with best technology and warranties to the industries.

CHALLENGES IN PROGRAMMATIC ENERGY EFFICIENCY DEMAND AGGREGATION

Demand aggregation and implementation of energy efficiency projects has number of challenges. Based on the project study carried out, our learning and key challenges are summarized below:

1. **Data Collection:** Collection of data is one of the major challenges in the demand aggregation process. Right from accessing the industries to the collection of data is a time-consuming process. Apart from this, availability of data is also a major concern in the SME sector. Very few industries do have available data which is required for energy study. Role of industrial association becomes very important as they have access to all the member industries and with their assistance, SME industries can be approached. Industrial association also helps in bringing member industries to one common platform.
2. Market Readiness: For the demand aggregation implementation, we reached out to 4 technology supplier companies (Air compressor and VFD) for large scale implementation. However, the responses from the air compressor companies were not encouraging. This could be due to either they are not willing to participate in such exercise or believe that such exercise will not generate enough business.
   For air compressor, the number of technology providers are limited with respect to the size of equipment. Small project size and limited vednors were the main reasons for not being able to implement demand aggregation.

3. **Initial investment in energy efficient air technologies:**
   Most of the SME industries have very limited budget and normally they invest in the projects (apart from expansion) if there is requirement from client for quality improvement. Investment in energy efficiency projects is last priority for most of the industries.
   This can be overcome by building confidence in the industries by doing some pilot projects and involvement of financial institutions.
4. **Quantification of savings:**
   In a SME industry, the variation in energy consumption is around 20-30% based on the productivity. Under this scenario, it becomes

very difficult for them to understand energy saving by a particular measure. Setting up of baseline for individual industry and making them follow it will ensure that energy savings are monitored.

CONCLUSION

When compared with large manufacturing industries, small and medium scale industries, have smaller scale of operations, smaller capital base, limited access to resources and efficient technologies. Our study provides insight about the energy saving opportunities, potential business model for scaling EE and challenges in implementing business model.
Compressed air system is one of the major energy consumer in an industry. We developed the understanding of demand aggregation process for programmatic aggregation of energy efficiency in compressed air system in automobile clusters.We leant about the challenges and limitations that could input for future efforts for similar projects in aggregate demand wi thin the MSME cluster. The learnings can be adopted to accelerate energy efficiency in SME sector.

Demand aggregation is an established way for accelerating and driving larger economies of scale if implemented methodologically. This not only results in reduced costs / or higher value from suppliers but also reduces costs of operations. Another benefit that accrues is of standardization which leads to inherent efficiencies.

It can be concluded that in a systematic and structured way, energy consumption in SME industries can be reduced by around 20-25% by implementing energy saving opportunities in compressed air system on demand aggregation basis.

ACKNOWLEDGEMENT

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Marathwada Association of Small Scale Industries & Agriculture (MASSIA). They have 1500 small and medium scale industries as their members. MASSIA supported us in data collection and connecting with their member industries.

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MANAGED ENERGY EFFICIENCY SERVICES FOR MANUFACTURING PLANTS

Pushkar Kumar[1], Ganesh Prabhu M[2]

[1] *Industrial Practise - Head*
EcoEnergy Insights
Toronto, Canada
pushkar.kumar@carrier.com

[2] *Industrial Practise - Presales*
EcoEnergy Insights
Bangalore, India
ganesh.muraleedhara@carrier.com

ABSTRACT

Traditionally organizations invest in software or applications with the objective to save energy and reduce operational expenses. Evolvement of technology has helped deployment of additional sensors and meters to be more cost effective compared to the last decade. These systems generate a large amount of data on a daily basis and it builds over time. Most organizations have limitations in terms of how to use this data effectively. In collaboration with a large discrete manufacturing client, EcoEnergy focused on effectively utilizing the data generated by these business systems and delivering insights to the customer. This enabled them to meet their sustainability targets and improve equipment performance. Along with the above technologies like **Big Data**, **IoT** (**Internet of Things)**, **Machine Learning**, **Analytics and Artificial Intelligence were also incorporated** in the project

This project was executed at a discrete manufacturing plant, spread over a 100 acre site, in the USA. For this client, our AI platform was used in conjuction with skilled analysts to focus on strategies to **reduce operational costs (maintenance and energy)**, **improve occupant comfort and safety,**for all of their HVAC/utility equipment. This combination of algorithms and analysts have allowed us to deliver over 5% of overall energy savings within a few months of project initiation with a payback of less than six months. The implementation also helped the plant team proactively identify future potential issues, thereby also helping better manage the chiller break-downs, among other things during peak summer month usage.

INTRODUCTION

At EcoEnergy Insights, a brand of Carrier , we use cutting edge technologies like AI, IoT, Big data and analytics to provide intelligent and sustainable solutions for enterprise-wide energy, maintenance, operations and efficiency management. We have designed and developed an AI & IoT platform to give predictive insights on equipment performance and help us offer such solutions. This platform provides insights to users around different operational issues (current and future) and proposes how to most optimally address them. The insights (on energy efficiency, mechanical improvement and other efficiencies) are available for equipment categories, like chillers, AHU or other HVAC components. We leverage our Command Center, an operations center with data scientist and analysts that can offer remote support as well, to uncover efficiency opportunities 24x7 and plug them in immediately. In terms of energy savings, we have saved our clients over 2.7 billion kWh in energy and counting.

The increased customer awareness about Greenhouse Gas (GHG) impacts has pushed manufacturers to further evaluate their operations and become more green. There are multiple ways to improve the GHG ratings, with one key being to reduce the specific energy consumption of the facility by focusing on non-core HVAC equipment and their operations. Such an approach not only reduces the GHG emissions but also improves the bottom line of the business, without disrupting core plant operations. The digital solutions targeting HVAC operations can be especially important in discrete manufacturing where HVAC/lighting/compressors can account for up to 60% of overall energy consumption, such as the case for the customer in this paper.

The customer's site was a large 100 acre discrete manufacturing plant, looking to quickly meet its sustainability targets without adding CAPEX costs. It was also looking for projects that can quickly support its implementation costs as well.

BACKGROUND

In past few years, falling commodity prices and a general slowdown in the economy has resulted in significant push to further optimize operational costs. The same was true with one large integrated discrete manufacturing facility where we have deployed our platform. This facility over 100 acre plant, also faced challenges in terms of frequent break down of its equipment and compliance issues in the utility section. This plant had 280+ non-core utility equipment (HVAC & lighting) apart from the 500+ core equipment in the production-process. Our solution focused on non-core utility equipment, for this plant.

APPROACH

For this large discrete manufacturing site, EcoEnergy Insights collected data from the repsective equipment/business systems and derived "Insights" from the data. "Insights" are nothing but actionable intelligence about an equipment or a system. All of the plant equipment was carefully provisioned to their virtual equivalent and the interaction among them was also carefully mapped. The platform is capable of collecting a variety of data streams over time, processing those streams, and applying data science tools and techniques, which was able to easily handle data from different sources, as was the case for this plant.

The prioritization of processesd data or "Insights" helped the customers to plan the activities and helped them in easy decision making. The result relies on the actions taken from these insights. Our analysts helped the customer by translating these "Insights" into work lists like the one as shown in Fig 3: They also discuss the implementation status and progress periodically to ensure that actions are taken. This approach helped this customer to realize the value of the insights and get the desired outcomes.

SOLUTION

The key aspect, during solution initiation, in a very large plant situation is to identify an area which is most likely to have savings impact prior to full rollout and then show early wins. We jointly focused on an area that consumes significant amount of, electricity and gas, so that any reduction in utilities cost will be immediately visible and thus make rest of the implementation more acceptable with all stakeholders. From the below it was clear that on an average utility equipment (HVAC/R & lighting) consumes 60% energy.

The equipment in the utility area included

i. Chiller – 4
ii. Air Handling Unit – 122
iii. Roof Top Unit Heaters – 45
iv. Pumps – 12
v. Variable Air Valves – 60
vi. Cooling Towers – 4
vii. Boiler – 1

Data Collection

EcoEnergy Insights then focused on pulling the relevant data for each equipment, carefully mapping their inter-relation and then continously pushing it to the IoT platform. To pull the data, EcoEnergy Insights deployed a connector software at the Building Management System and the site's Energy Management System. The platform collected data at every 15 minutes and then stored it in the cloud. Once provisioned and the data flow established, the platform then used AI to find issues, depict them properly for easy operator usability and provide actionable insights.

Periodical Work Lists :

Key Performance Indicators (KPI) were identified and mutually agreed upon with the customers and dashboards were used to monitor the performance over time. The work list is a summary of deviation and improvement opportunities identfied and priotized by the platfom. These work lists helped the plant maintenance manager to plan the activities in an efficient manner.

The AI driven performance data analysis then not only predicted issues before the equipment fails, but also helped the maintenance manager by way of recommending actions to see whether the particular issue has been resolved or not and thus ensure the effectiveness of the maintenance activity. For this customer, work lists were then shared and discussed fort-nightly.

Deriving proactive actions:-

Insights are NOT alarms. AI based algorithms are used to drive predictive intelligence to help proactively manage equipment BEFORE problems become alarms. Algorithms have a large repository of past failures and issues and continously look for the data based issues. This approach has helped provide a much wider response time window, prior to the situation becoming critical.

The platform uses unique and patented equipment-oriented algorithms to represent the true state of the equipment in the virtual environment and hence drive proactive actions to eliminate break downs.

DELIVERY METHODOLOGY

As explained in the solution there are multiple ways with which we have engaged with the plant team to deliver the results. Below are the few samples:

Sample Performance view

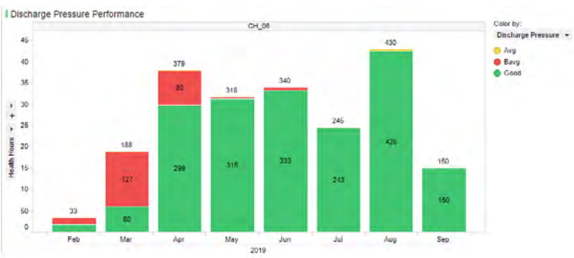

Figure 1: Sample Performance View

The above dashboard explains how the data collected from a chiller was transformed into insights. The above diagram displays the discharge pressure condition on a monthly aggregated basis and indicates the hours of Good (Green), Average (Yellow), Below Average (Orange) and Others (Grey). "Good" (Green) is considered as the ideal or recommended operating conditions for the equipment. The "Average" (Yellow) gives the indication that, the performance parameter needs improvement and "Below Average" (Red) requires immediate attention.

The predefined and patented algorithms helped the platform to determine and categorize the true nature of the equipment. The analysts at the Command Center used this information combined with related other information to identify the root causes and report to this customer.

Because of clear dashboarding, the improvement was also very evident, where the outcomes depict that "Below Average" conditions were eliminated beyond the month of April – which was made possible by resolving the issue on the chiller sequencing.

Sample Advance Analytics

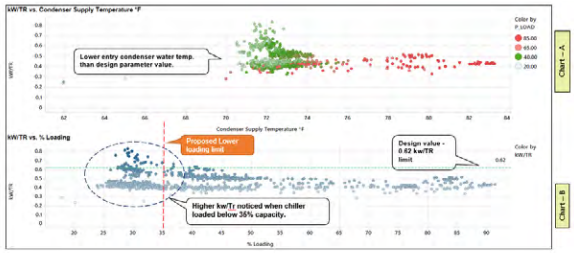

Figure 2: Chiller efficiency analytics

The above is an example of advanced analytics output in which an analyst derived actionable insights combining different visualisations for this client. Chart A shows the condenser supply water temperature vs kW/TR colored by chiller loading % and Chart B shows loading % vs derived kW/TR for the analysis period. It was observed that chiller#6 kW/TR is ideal above 35 % loading conditions and entry condenser supply water conditions greater than 74*F. However high kW/TR was noticed at low load condition (less than 35%) along with lower condenser water inlet temperature. The actionable insights from the above was to limit the lower loading limit to 35% and set the lower condenser water temperature limit to 74 *F for higher chiller efficiency.

Sample Work List

ID No	Asset Type	Insights Type	Key Observation	Recommendation	Target Assets	Estimated Saving / Yrs. (kWh / $)	Estimated Savings /Annual ($)	Estimated Saving CO2e MT	Potential Impact	Prioritization
1	Chiller	Chiller Availability	It was noticed that CH#03 differential oil pressure during operating conditions were noticed lower than the low limit range (20 kpa).	Possibility of low oil pressure in the system would have caused the chiller to trip for protection.	Chiller -03				High	High
1	Chiller Plant	Chiller Proactive Efficiency	• Centrifugal chiller#03 with higher capacity is operated at part and low loading condition(30 to 60%) which is resulting in higher kW/TR (0.7 kW)	Review the Chiller plant controls logics and to sequence the chiller#4 for low cooling load requirement with higher loading condition.	Chiller System	16,697	$1,336	9.03	Medium	Medium
2	Chiller Plant	Chiller Proactive Efficiency	• Condenser Water differing from the set value even though OAT Wet bulb is favorable. Also CT Fan speed is constant100%	Check the Possibility of effectiveness improvement at cooling tower	Cooling Tower_06	1,409	$113	0.76	High	Medium
3	Boiler	Boiler Proactive Efficiency	• Boiler is enabled for OAT greater than 65°F during Occupied hours and greater than 75°F during unoccupied hours.	Check for any overrides and release for operation inline with present logic.	Boiler System	2679	$214	1.45	Low	Medium
4	AHU	AHU Proactive Compliance	• The space temperature is not maintained as per the policy for few assets and hence there is overcooling & undercooling scenario noticed.	• Implement the unoccupied schedule • Check the interlock logic of unit operation with set points • Suggested to maintain the uniform set point for the assets in same zone	AHU System	448,300	$36,223	242.53	High	High
5	RTU Heater	RTU/MAU _thermal compliance study	The space temperature set point is deviating from the ideal/desired set point and with different set point across assets, which results in thermal discomfort to the occupant.	• Implement the unoccupied schedule • Check to see the possibility of changing the unoccupied set point to 60-62°F for the unoccupied period instead of 55°F which is observed in most of the assets • Suggested to maintain the uniform set	RTU System	247,570	$20,000		High	High

Figure 3: Work list - sample

The above provides a sample work list which is a summary of deviation and improvement opportunities identified by the platform. The potential impact and prioritization was provided for each problem so that it becomes easy for the plant operations manager to take up the corrective actions.

Most of the recommendations from the platform are related to the operational issues and usually does not require any capital investment other than control technician requirement at the site. This customer was also provided an estimation of projected savings (annually) for easy decision making process. Overall the work list acts as an additional management tool for the maintenance manager to manage their equipment operation effectively.

RESULTS & BENEFITS

The results of the project were exemplary and key being the following:

1. Digital representation of the equipment was created that reflected, in near-real-time, the current health condition, predicted issues and presented insights
2. Reduction in Energy & Gas consumption helped them to meet the Sustainability targets (achieved 6.42%) for the plant Reduction in Energy & Gas consumption helped them to meet the Sustainability targets (achieved 6.42%) for the plant.

Connecting the Equipment to Plant Team : Real-time information coupled with cloud-based analysis enabled by our approach, helped the plant manager to understand the health and performance of each and every piece of equipment. This enabled the plant utility managers to get a better view of the utility equipment.

Improving the Operational Efficiency of the Utility Equipment: The platform collects data from the Building Management and other systems every 15 minutes and is stored in the cloud. Analysis of the real-time performance data is enabled to take proactive actions before the equipment fails, but also deal with any compliance & efficiency issues

The short summary of the first six months are showcased below. For easy understanding the energy & gas consumption are converted into respective CO_2 equivalents. The 2018 data (first 6 months) is considered as a base line . The standard normalization process is applied for Weather and Production data to reflect the variation

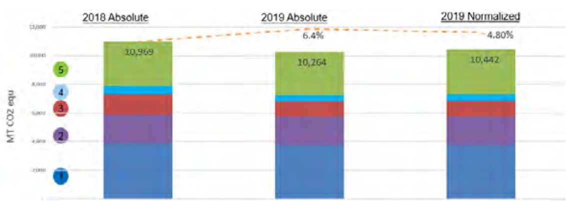

Figure 4: Savings Summary -1

Type	Absolute 2018	Absolute 2019	Normalised 2019
Electricity for Production - CO_2 e	3,063	3,019	3,130
Gas Heating - CO_2 e	616	421	462
Electricity for Cooling - CO_2 e	1,418	1,081	1,106
Gas - Baseline - CO_2 e	2,035	1,983	1,983
Electricity - Baseline - CO_2 e	3,836	3,760	3,760
Total CO_2 Equvalent (MT)	10,969	10,264	10,442
% Savings in CO_2 e	-	0	5

Figure 5: Savings Summary-2

CONCLUSION

The Manufacturing sector has sufficient data available in its systems for effective use of data driven efficiency measures. However data analytics alone will not yield a desired "efficient outcome". A successful implementation needs an implementation partner who can work with multiple online & offline data sources And effectively model it for proper usability and remote management and then present the solution in a way that it can be quickly adapted without much disruption.

The discrete manufacturing industry, which is a key manufacturing format in India, can have as much as 60% of energy consumption in non-core equipment. This equipment can very easily be targeted for quick energy consumption reduction without touching any core production process and at minimal CAPEX costs

Typically, the manufacturing organizations can easily reduce upwards of 5% of energy costs; reduce over 5% of maintenance costs and improve upon compliance /quality, as was the case for the plant in consideration for this paper.

NOMENCLATURE

HVAC – Heating, Ventillation , Air Conditioning
R - Refrigeration

SCADA = Supervisory Control And Data Acquisition

IoT – Internet of Things
BMS – Building Management System
BAS – Building Automation System
RTU – Roof Top Unit
VAV – Variable Air Valve
AHU – Air Handling Unit
GHG – Green House Gas
KW – KiloWatt
TR – Tons of Refrigeration
AI – Artificial Intelligence
CO_2 – Carbon Dioxide

AN ONLINE TOOL FOR ASSESSMENT OF HARMONICS AND REACTIVE POWER TO PROMOTE ENERGY EFFICIENCY & REGULATORY COMPLIANCE IN INDIAN INDUSTRIES & OTHER DEVELOPING COUNTRIES

Rajen Mehta[1], Manas Kundu[2], Kartik Parekh[3]

[1]*Efficienergi Consulting Pvt. Ltd.*
Mumbai, India
rajen@efficienergi.com

[2]*International Copper Association India*
Mumbai, India
manas.kundu@copperalliance.asia

[1]*Efficienergi Consulting Pvt. Ltd.*
Mumbai, India
kartik@efficienergi.com

ABSTRACT

Traditionally, the Power System used to serve majorly only linear loads on the receiving end.
However, with the advent of industrialization, to achieve better energy efficiency as well as clean power alternatives, the characteristics of the load gradually transitioned to a non-linear one, most noteably variable frequency drives, inverters, SMPS based loads among others.
These loads are known sources of high harmonics and thus more losses while their coupling in traditional power system network makes it prone to many other unpredictable side effects such as malfunctions, tripping etc.
The nature of such loads is rising dramatically thus bringing with it the associated side effects at a much larger level.
For end user awareness, it is important to identify these issues and its effects along with mitigating solutions. Whilst various stakeholders such as OEMs of mitigating solutions, utilities through regulations continue to spread awareness on them, the need to have a quick user friendly reference on the impact of poor power quality especially harmonics and poor power factor is very much there. At the same time it needs to link directly with energy efficiency / losses / ROI for the industry to take action faster.

The paper is an attempt to highlight the science behind the release of an online open access assessment tool (for Harmonics/PF) for the benefit of industries, MSME's as well as utilities. While the tool dispels actionable insights relevant to all Indian consumers and provides state specific insights, it also can be adapted to suit other developing country needs with minor changes.

Keywords—harmonics, non-linear loads, power factor, losses, energy efficiency, online tool *(keywords)*

INTRODUCTION

The cost of Power Quality is a topic which has been researched through numerous papers and case studies and surveys. On the economic front it can be classified as

- Loss of Revenue
- Tie up of equipment capacity
- Increased Electricity Bill
- Loss of Opportunities

At the same time it is also challenging to evaluate the same considering it comes from different areas such as

- Downtime – Revenue per hour and cost of production
- Equipment Problem – Troubleshooting the root cause and determining the actual costs
- Energy Cost – Actual power, reactive power (PF) penalties, and MD charge structure

The end consumer at present is more prone to the effects of power quality and related issues with the prominent ones apart from voltage related being harmonics and poor PF. The equipment has become much more sensitive to power quality problems than these have been earlier due to the use of automatic controls, power converters, which are highly sensitive to the quality of supply and other disturbances. The distribution system also gets badly affected by the non-linear loads especially critical network infrastructure such as distribution/power transformers and cables. These loads are responsible to inject harmonic currents in the main power supply which create chain reaction of undesirable events. Apart from generating harmonics, these non-linear loads need reactive power and thus creates unbalance which increases the severity and may cause additional problems like derating of cables/feeders, and may impact operating PF as well. They may elevate the losses in transformers, cause equipment malfunction, oversaturate neutral, etc. These effects of harmonics and other PQ issues are well documented in many referenced papers and case studies.

The severity of PQ nationwide is buttressed from the study conducted by the Power Grid in 2015 which gives following statistics:

Zone	% of time PF < 0.8
North	24
East	22
South	10
West	6

Feeder (kV)	% of time PF < 0.8
220	20
400	37.5
765	55

Figure 1: Statistical data deduced from Swachh Power Report-2015

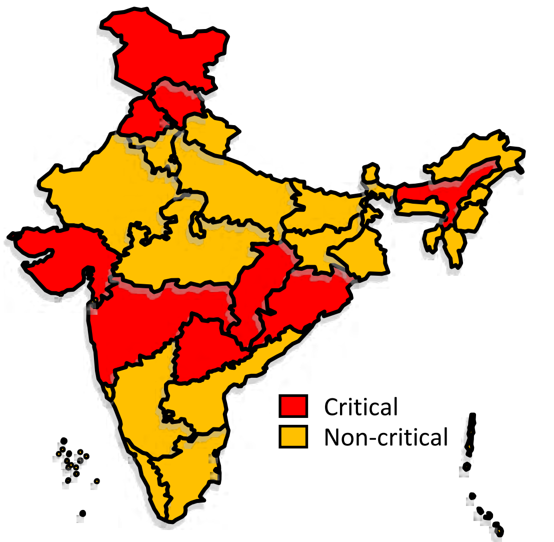

Figure 2: Power Quality Map of India - Swachh Power Report-2015

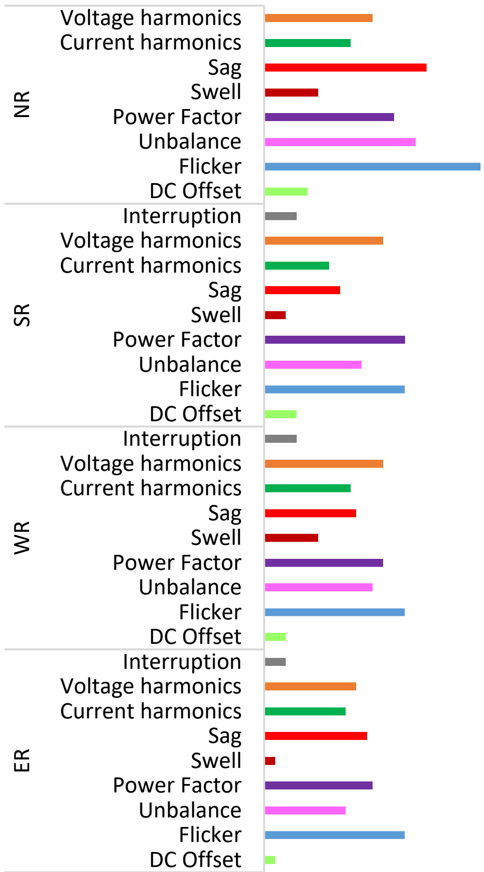

Figure 3: Region-wise Power Quality Parameters observed across the country - Swachh Power Report-2015

The above study clearly summarizes that even with reactive power compensation being so widely promoted through incentive / penalty mechanisms by state distribution companies, still Power factor remains at a much lower level nation wide. It also highlights the criticality of the PQ nationwide which presumably has worsened further in the next 3-4 years after this study has been conducted.

The awareness related to harmonics and PF related problems has increased among the customers due to direct and indirect penalties enforced on them, which are caused by interruptions, loss of production, equipment failure, regulatory standards, tariff structures and so on. While the issue related to harmonics has become popular in past few years, huge efforts are still required to mitigate the associated impacts as quantification of the effects is not easy.

For the better addressal of the problems pertaining to the harmonics and PF, an open access tool, 1st of its kind, has been developed with support from Asia Power Quality Initiative APQI - a neutral platform working to build awareness & capacities on issues

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related to Power Quality so as to provide quantified metrics thus giving helping hand to resolve the unattended issues of the end-consumers. The tool addresses the issues of each and every stakeholder in a plant/facility related to harmonics and poor PF. While CXOs are concerned for extra incurred costs due to energy losses, the Plant Heads are focused to mitigate penalties/losses/repairs due to PF and harmonics. The tool is capable to suggest user by giving not only technical and business metrics but anti-punitive measures as well. It leverages state-specific norms and is in-line with latest relevant standards like IEEE 519-2014.

METHODOLOGY : TOOL INPUTS, OUTPUTS AND ANALYSIS

1. Key outputs from Tool

- **a)** Determine the KVAR requirement to reach optimum Power Factor and perceive achievable savings from avoidable energy costs.
- **b)** Estimate maximum allowable load capacity of the transformer based on harmonic derating.
- **c)** Identify the estimated compatibility to latest harmonic standards like IEEE 519-2014.
- **d)** Gauge cable and transformer losses due to harmonics.
- **e)** Obtain estimated budget for harmonic mitigation and PF improvement
- **f)** Estimate harmonic distortion with/without harmonic measurements

2. How to determine the KVAR requirement to reach optimum Power Factor and perceive achievable savings from avoidable energy costs?

Because of increase in fundamental and non-fundamental reactive power in electrical network, the equipment connected to that network will draw high currents from the electrical system.
In a non-harmonic system both the current & voltage are sinusoidal. The apparent power is the vector sum of the active and reactive power and represents the complete burden on the electrical system. But in a harmonic condition that is produced by nonlinear loads, the kW / kVAR spectra contain many of the harmonics in current.

To save on costs related to this invisible distortion component that affects both kwh and kVAh consumers, (although much significantly on kVAh consumers), we need to consider both fundamental and non-fundamental elements to calculate the total KVAR of network and the total additional KVAR required to get the optimum power factor of the system as follows

$$\text{Total KVAR}=\sqrt{\text{KVAR}^2+\text{KVAR}_N^2} \qquad (1)$$

Where KVAR is fundamental component and KVAR_N is non-fundamental component of the network.

This tool will calculate the required KVAR with help of load current and Power Factor as inputs to the tool. Since nowadays there is transition from the Displacement Power Factor to the True Power Factor, hence keeping that in mind the tool can accept either as input. The KVAR proposed by the tool is in sync with harmonic Mitigation proposed and not in isolation.

The tool also provides overview to the user for the losses before and after the installation of suggested filter. More details on those are explained in Section 5 below. Example of the same can be seen in the case study mentioned in the latter section of the paper.

3. How to check if you have compliance as per IEEE 519-2014?

Identifying the compatibility of harmonics in a power system is a big challenge now a days and this is considered as a joint responsibility involving all the stakeholders including the end-users. Harmonic limits are recommended for both voltages and currents. The underlying assumption of these recommended limits is to limit the harmonic current and voltage injected by end-users. In the event that limiting harmonic currents and voltages alone does not result in acceptable levels of distortion, end-users or operators should take action to modify system characteristics so that voltage distortion and current distortion levels are acceptable.

We can characterize current distortion levels with a THD value, but this can mislead the end user in the selection of harmonic filter. Small currents can have a high THD but cannot be a significant threat. For example, many adjustable-speed drives, pulse converters will exhibit high THD values for the input current while operating at light loads. This shouldn't be a concern, because the magnitude of harmonic current would be low in that instance, even though its relative current distortion is quite high. Responding to such scenarios, this tool will analyse fundamental of the *peak demand* load current rather than the fundamental of the present demand. As per guidelines of IEEE 519-2014, TDD and not THD

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serves as the basis for evaluating compliance. This tool will analyse the TDD where *IL* is the maximum demand load current over last 12-month average measured at the point of common coupling (PCC), which is usually at the customer's metering point. As it simply states that TDD is equal to the square root of the sum of squares of each of the maximum demand currents from the second harmonic to the maximum harmonic present, divided by the maximum demand load current at the fundamental. TDD is meaningful when monitored at the PCC over a period of time that reflects maximum demand of the customer as Per IEEE 519.

The main function of Tool is to design Harmonic filter for electrical network. It does so by including harmonic voltage limits and current distortion limits. **More importantly the size of the filter is guided by the compliance requirement of TDD as opposed to bulkier filter sizes that would be required if only THD-I was considered.** The measure of size is determined by a ratio called the "short-circuit ratio," or SCR, which is the ratio of the maximum *short-circuit* current at the Point of common coupling (PCC) to the maximum *load* demand current (IL) of the fundamental at the PCC. An attempt is made to calculate an estimated short circuit current at the PCC using different methods depending on the input data provided. In the first method this short circuit current can be calculated from the input data given by the user like short circuit MVA and Base KV with a formula as follows

$$\text{Isc}=(\text{Fault MVA})/(\sqrt{3} * \text{Base KV}) \quad (2)$$

In absence of available short circuit MVA which is generally difficult to obtain alternatively Isc is calculated with help of line voltage drop and %Z.

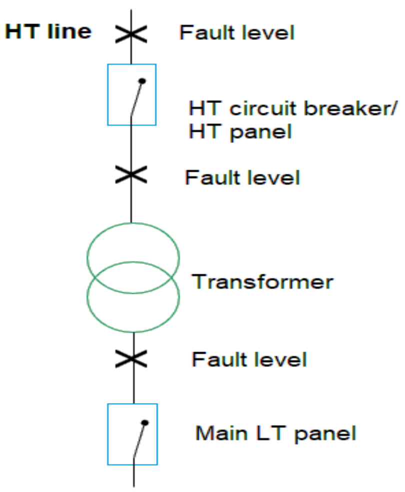

Figure 4: A Typical Electrical System SLD

Isc calculations are done either for LT or HT network. In Fig 4 is simple SLD of the electrical network where fault MVA is unknown. LT cable between the HT line and LT breaker is taken into consideration. The tool itself calculate the %Z for that block with the help of R, X, cable parameters, and voltage drop. With help of the %Z, tool will calculate Fault MVA as follows.

$$\text{Fault MVA}=(\text{Base MVA})/(\%Z) \quad (3)$$

Now to achieve these voltage harmonic and current harmonic limits, IEEE 519 sets limits on the amount of harmonic currents injected into the PCC, as a function of the size of the load. Following tables from IEEE 519-2014 are reproduced which are utilized for compliance verification by the tool.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \le 1.0$ kV	5.0	8.0
1 kV $< V \le 69$ kV	3.0	5.0
69 kV $< V \le 161$ kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Figure 5: Voltage Distortion limit table from IEEE 519-2014

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Figure 6: Current Distortion limit table upto 69kV from IEEE 519-2014

Compliance results from the tool are obtained from values computed either by Reference Library data or Measurements entered by the end user.

With the help of the proposed filter current spectrum, projections on remaining harmonic distortion can be obtained.

The norms related to PQ are prevalent in US and European countries. While Indian sub-continent so far had focused mainly on availability of power, the upcoming trends and future projects mandates a similar regulation. The concerned bodies like BIS are working to introduce PQ regulation in coming days. By the time it is introduced, user can verify in advance whether their facility or part of their facility comply to relevant national/global standards or not.

4. What is your Cable and Transformer losses due to Harmonics?

The true power transferred to the load is a fundamental component of the system and whenever the current drawn by the load contains harmonics the total RMS current will be greater than the fundamental.

$$Irms = I_1 \sqrt{1 + THDi^2} \qquad (4)$$

The above fundamentally explains that the total losses will be contributed by the sum of all the losses at all the individual frequencies.
These losses in the system increase the temperature in case of transformers and cables. In case of transformer generally losses in windings increase as the square of the THDi and that core losses increase linearly with the THD_u.In Utility distribution transformers, where distortion levels are limited, losses increase between 10 and 15% approximately.

The losses due to fundamental and non-fundamental currents in the transformer are as follows

$$\text{Total losses}=\sqrt{(I^2*R+(I_n)^2*R)} \qquad (5)$$

Where in the above equation *I* is the fundamental component of current and I_n is the non-fundamental component of the current

Total load losses in the transformer will be represented as

$$P_{LL}=P_{ec}+P_{osl}+P_{dc} \qquad (6)$$

Where
P_{LL} =Total load losses
P_{ec} = Eddy current losses in winding
P_{osl} = Stray losses in parts of transformer
P_{dc}= Ohmic losses

Ohmic losses are calculated by considering the winding impedance of transformer and connected load.

Pointing to eddy current losses these losses are produced due to time varying nature of magnetic flux in the transformer. Drawing upon IEEE C57.110 and assumptions using practical thumb rules such as.

$$P_{ec}=0.33\ P_{osl} \qquad (7)$$

$$Pec = 0.33\ Posl$$

for oil cooled transformers, the tool arrives at practical estimates of the additional losses due to non-sinusoidal quantities with minimal information. At the same time it also calculates the % of derating of transformer due to harmonics i.e. Factor-k. defined as weighting of the harmonic load currents according to their effects on transformer heating, as derived from ANSI/IEEE C57. 110.The higher the Factor-K, the greater the harmonic heating effects.

Cable losses are also additionally calculated based on cable data entered or assumed based on loading as well as minimum short circuit withstand capability. The additional losses due to non-sinusoidal currents play a bigger role and the active plus reactive power due to harmonics are calculated to arrive at these losses in cables as well.

To understand more in detail, we will see one of the case studies conducted by a textile mill located in the Maharashtra region using this tool.

5. Estimate harmonic distortion with / without harmonic measurements

If the user does not have harmonic data through measurements available, the tool has a capability to calculate and simulate the effect of total harmonic distortion based on the standard harmonics spectrum and inbuilt designed libraries for 6 pulse VFD drives, UPS and Lighting loads. These are simulated together to provide the combined effect at the PCC so that preemptive action can be taken at greenfield or expansion stage in terms of mitigation strategy to be planned. Work on augmenting the library remains a continuous process to be able to have more and more different kinds of non-linear loads as well as additional ratings, makes and models.

DISCUSSION AND RESULTS ANALYSIS : A CASE STUDY

The client belongs to *Textile industry* and relevant data like per unit energy rate, operating hours, L-L network voltage, type of conductor, size of conductor, voltage and current harmonic data, etc.

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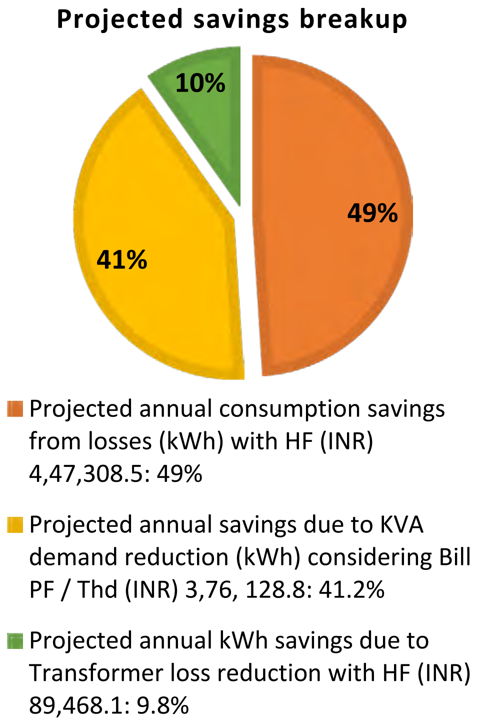
was fed as input. The facility had a 2500KVA transformer and the maximum demand was about 1279KVA with voltage harmonic distortion at about 8% and current harmonic distortion at about 42% and following takeaways were obtained:

1. They found that the estimated harmonic compliance at PCC as per IEEE 519-2014 standard was above standard limits.[1]
2. The tool provided them key findings, corresponding impacts and recommendations along with projected monetary benefits.
   For e.g.
   - **a)** They found that I-TDD% and V-THD% were above limits as per the estimated IEEE 519-2014 compliance[1].
   - **b)** The tool also made them aware of possible impacts of the findings like possible regulatory penalties, possible overloading/overheating of network element, possible network resonance. It computed the total kW Loss: 17.23 kW, total kVA Loss: 50.71kVA, transformer additional kW Loss: 6.164 kW.
   - **c)** Also, it gave them prioritized recommendation to come in-line with the compliance requirements as well as to save on losses in the facility

     Phase-I:
     Based on Measured/Bill PF, provide Additional 175 KVAR with 7% Series Detuned Reactor

     Phase-II:
     Provide 550 Amps Active Harmonics Filter (HF) to improve distortion PF.
   - **d)** The tool projected kVA Demand Reduction by improving PF (Billed / Measured) and Harmonics to be: **125.38 kVA** & Recoverable Total (Line/Load + Transformer) kWh Loss with Harmonic Filter and Capacitors ON to be: ***75924 kWh/Year***
3. Based on Factor-K calculations it suggested to derate the transformer to 91.9% of its full load capacity. So, in effect the 2500KVA transformer can be loaded only up to 2297.5KVA due to the harmonics present.
4. The tool also suggested the estimated annual savings of ***INR 9,12,906*** along with the ROI of ***2.7 yrs***[2] thus enabling the management to take an informed decisions of further detailing if required.



5. The tool also gives projection of achievable V-THD% and I-TDD% with HF which in this case were 1.9% and 7.4 % respectively.

CONCLUSION

The tool is first of its kind attempt especially by remaining extremely user friendly for a normal maintenance engineer and can succeed only with the active contribution from various stakeholders. This tool aims to bring down the resources spent on the Power Quality/PF studies only to give a better proposition in terms of tangible/in-tangible value to

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[1] The compliance is obtained by applying IEEE 519-2014 on a single timestamp measurement snapshot. However, for accurate compliance IEEE 519 requires data over extended period of time to ensure statistical significance of the outcomes

[2] The savings and ROI calculations are a guestimate based on some assumptions of the facility as well as benchmarked filter rates. The same are just provided to give an indication and are in no way an accurate estimate since savings as well as ROI depend on a number of factors apart from just losses

the end user and to provide as a quick decision tool to take action further and dive deeper if warranted. Much more can be done to enhance the accuracy and estimates from the tool by modeling additional system components as well as the recommendations thrown to incorporate more technologies as well as mirror real life cases better.

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MARKET CHANGES AND EXPECTED SOLAR PV POWER PLANT OPERATIONAL HURDLES AND APPROACHES TO REDUCE ITS IMPACTS FOR BETTER ENERGY ASSET MANAGEMENT

Dibin Chandran

Center for Solar Energy
World Institute of Sustainable Energy
Pune, India
dibinchandrannair@live.com

ABSTRACT

Indian solar PV installation reached 29GW on May 2019, and its chasing 100GW ambitious target. Parallel with this exponential improvement in the solar EPC market, it is expected that the solar PV O&M market is also will grow up. Since the solar PV industry is moving fast in terms of technology and innovations, power plant components available in the market are improving rapidly. Also, some technology has been obsolete from the market, this may be due to, change in technology and/or OEM's production line. capacity considering future changes. From the close observation on this rapidly changing market it was observed that the PV and other BoM technologies that presently available in the market has changed extensively in past 10 years. This may introduce operational issue in terms of lack of spare parts availability, compatibility issue of available components, etc. in future. For the smooth operation of power plant it is necessary to make sure that the maintenance will not face such hurdles in the future, which demands properly framed policy and/or regulations pointing the strategic deployments PV capacity considering future changes. This research study covers the analysis of technology transformations in the solar PV industry in past and how it affected the market and also trying to interpolate this to current scenario to suggest strategy to be adopted for smooth operation in future. This paper intends to give insights about rate of changes in the PV market scenario, expected SPV O&M market and its spare parts required, the effect of technology change in the PV O&M market and recommendation to reduce plant downtime.

Keywords—EPC market, PV, Technology, O&M, Downtime

INTRODUCTION

Considering the current accelerated deployment of solar PV, grid base power may shift from conventional thermal sources to renewable energy. Unlike conventional power generation, PV technology has a gradual degradation in power generation. This situation may impose high demand v/s generation fluctuation in utility grid, if grid's base power is from non-conventional power generation. Hence, along with aggressive capacity addition, adequate efforts are required to ensure the effective operations of these power plants. In India MNRE has published a target of 100GW on-grid solar PV power plant installation by the year 2022 (MNRE, 2014). Considering target of 100GW and smallest power plant capacity (1kW), it is evident that the total quantum of power plant will be very high. So strategic approaches are required to manage these large quantum of power plant which distributed all over the country.

Figure 1 shows graphically on expected v/s actual solar PV installation under national solar mission (NSM). Considering the actual rate of PV implementation and its targeted rate, it is expected that the rate of implementation needs to be accelerated to achieve expected 100GW, i.e, aggressive solar PV implementation in short span of time is required. Due to this ambitious target and short period of time, there is a chance that the quality of materials and installation may get affected. By the implementation of mandatory quality checks before installation MNRE is trying to avoid this issue. Even after following all technical standards during installation, some minimum operational requirements need to be carried out to achieve expected output from power plants.

As per Central Electricity Authority (CEA) India's peak electricity demand and electrical energy requirement is going to become 225.751GW and 1566,023 MU respectively in 2021-22 (CEA, 2018). Considering the 100GW targeted solar PV capacity and projected electricity demand, solar PV is expected to contribute a major share in total power generation. Adequate efforts should be taken to get expected output from solar power plants such as:

- Consideration of O&M during design
- Proper monitoring system
- Strategic O&M planning and performance analysis
- Spare parts management
- Implementation of Environment Health Safety (EHS)

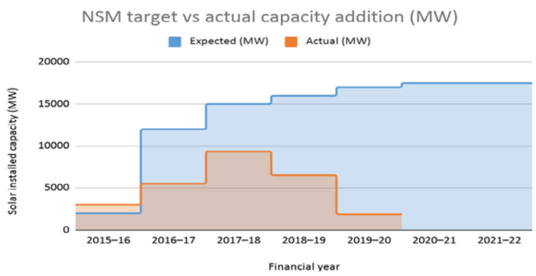


Figure 1: National Solar Mission(NSM) yearly target vs actual capacity addition (MW) (CEA, 2019)

Considering the accelerated solar PV power plant implementation, it is expected that the solar O&M market will also take up. Consider **Figure 2** which indicating expected O&M market as per NSM implementation target. By considering installed power plants before 2015 and NSM target, it was expected that 17.7GW of power plant will be 5 years old or more by year the 2022. Here a 5 year threshold is taken because all other electronic components including workmanship, having a 5 year warranty from OEM and EPC (except PV panel). So, it is evident that 17.7 GW power plant needed more attention in terms of O&M requirement by year 2011-22 (CEA, 2019) (MNRE,2014). This shows that there will be an unavoidable gap between installed capacity and actual capacity in GW available for power generation. Which can be optimized only by adopting effective O&M.

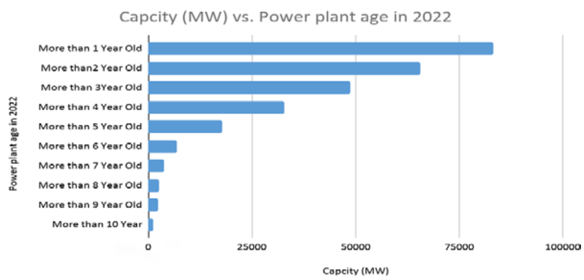


Figure 2: Expected solar PV O&M market

Addressing the above issues, performance and operational activities of around 112 numbers power plants are studied. It was found that, under performing power plants shows common problems in terms of asset management, technical issues. Following sessions in this paper discuss consolidated facts that were observed and recommendations made for proper O&M management.

O&M CONSIDERATIONS IN DESIGN

Solar PV power plant design starts with a feasibility study followed by design engineering. Plant design which enables provisions for operational activities will improve quality O&M (eg: **Figure 3b)**. It was observed during the site analysis that those power plants which neglected O&M provisions are facing a gradual drop in CUF (eg: **Figure 3a)**. **Table 1** shows general O&M consideration and its effect on CUF of 51 numbers of power plants (under performing or CUF ≤15%).

Figure 3: Power plant with (a) No access to far end PV arrays, (b) proper walkways for accessing PV arrays

Missing design points which supposed to be considered	**Average Minimum CUF (%)**	**Average Maximum CUF (%)**	**Commonly observed faults**
Accessibility to plant area	9	12	A, B, D, E, F
PV plant cleaning provisions like piping arrangements	9	11	A,B,E,F
Monitoring systems	8	13	B, D, F
Quality Assurance Plan (QAP) for proper project management	10	15	E,F
Designing the system considering future hurdles (eg: considering future building construction which may cause shadow)	4	13	C,F

A.Soiling, B.Blocking diode failure, C. Shadow, D.String connection failure, E. PV panel failure modes, F. Accelerated degradation of PV panel

Table 1: Relationship between points to be considered during design, CUF and commonly observed faults at PV plant area (Anand W, 2019)

Like any other component which a have direct relationship on plant's O&M, monitoring systems plays an important role in asset management. Consideration of proper monitoring systems will help the asset owner or the O&M team for easy adoption of preventive and corrective maintenance during the plant operation. Selection of monitoring system needs to follow IEC-61724: Photovoltaic system performance – Part 1: Monitoring. Monitoring systems need proper O&M otherwise it may lead the asset owner to significant financial loss. It was observed that, monitoring systems of around 47% power plants are either not functioning or malfunctioning from 3rd year onwards.

Figure 4: Soling on irradiation sensor leads to error in performance monitoring of power plant

OPERATIONAL ISSUES OF SOLAR POWER PLANTS

Solar PV power plants having less operational requirements compared to other power generating technologies. However, strategic approach in O&M needs to be adopted to avoid operational hurdles, which in turn needs proper monitoring systems. Type, specification, accuracy class and the number of monitoring systems required will vary as per capacity of power plants (IEC 61724-1, 2017). **Figure 5** and **Table 2** shows power plant's data acquisition points:

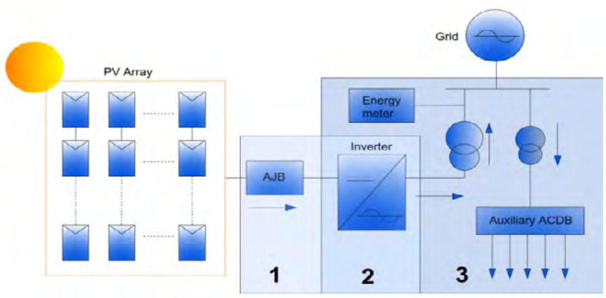


Figure 5: Solar PV power plant data acquisition points

Unlike other power generation technologies, fault in solar PV's power plants will not show significant generation variation during the initial stage. If the situation continues for a long time, the fault may get built up and after some time the power plant will start showing significant generation loss, and most of the time it might be irreversible. By adapting proper operational procedures and analysis of monitoring data these situations can be avoided.

Parameters and purpose of measurement
1. Array level measurement Array voltage DC (V_{array}) (V), current DC (I_{array}) (A), power DC (P_{array}) (W) • String level power monitoring, fault identification. • Measurement taken using AJBs with string level monitoring. • Commonly used in utility scale power plants with central inverters. • Fault identification is easy for wide spread utility scale power plants having string level monitoring.
2. Inverter level measurement Inverter MPPT voltage DC (V_{MPPT}) (V), current DC (I_{MPPT}) (A), power DC (P_{MPPT}) (W) Output voltage AC (V_{out}) (V), current AC (I_{out}) (A), power AC (P_{out}) (kW, kVA, kVAr), Energy (E_{out}) (kWh) Power factor, Frequency (Hz), Temperature • DC measurement is used for calculating DC losses, fault identification. • AC and DC parameters can be used to calculate the system's performance. • Power factor, frequency, active/reactive power output, voltage, etc., are measured to monitor power quality related compliance. • Inverter level monitoring is used to record instantaneous and cumulative generation.
3. ACDB/Grid-level measurement Grid voltage (V_{grid}) (V), Power factor, Frequency (Hz), Energy total (E_{out}) (kWh, kVAh, kVARh) • Instantaneous/cumulative power injection for monitoring total plant generation or export to grid. • To check grid electrical parameters. • Energy recording for backup measurement of energy meter. • Events' logs (grid failures, plant start/stop time, overvoltage, extreme/fault events etc.

Table 3: Solar PV power plant data acquisition points

Some of the commonly observed operational issues and analysis methods are:

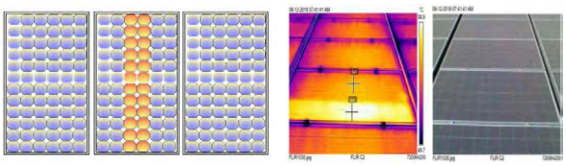
- **Shadow, Soiling**: Visual observation, generation analysis
- **Inverter failures**: Regular inverter log checks, inverter parameter checks, generation analysis, IR imaging
- **PV panel failure**: Visual observation, IR imaging, IV tracing, Voltage/current measurements (string and PV panel level), generation analysis

PV panel failure modes are not easy to identify only by analysing generation, this also needs continues preventive maintenance using instruments like IR camera, IV tracing etc. Further the analysis requires advanced testing like EL imaging, degradation analysis, etc. Some of the PV panel failures observed at the site and its identification using IR imaging and IV curve listed below.

IR image and IV curve results and failure causes

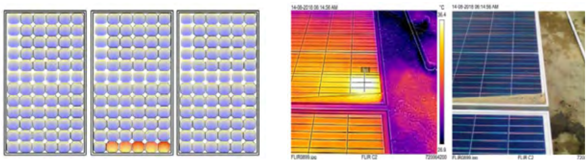
- **Significant temperature variation in PV module sub-array.**

Short circuited bypass diode: This can be caused by continuous thick shadow/hard soiling on solar module or short circuit inside the module junction box.



- **Hot spots at bottom edge of the module (towards lower end)**

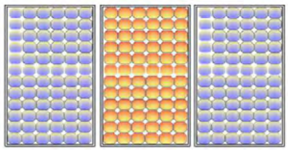
Shadow caused by soiling scale formed because of improper cleaning



- **Significant temperature variation in PV module.**

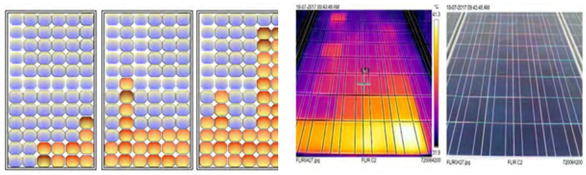
Bypass diode short circuit/failure: This can be due to continuous thick shadow/hard soiling on solar module and / Short circuit inside the module junction box.

In case the PV module is disconnected or isolated from the circuit, those modules will show higher temperature than normal modules.



- **Increased hotspot towards negative end of the string**

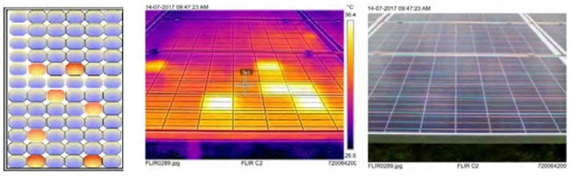
Shunting caused by charge accumulation on cell surface or PID effect



- **Shattered hotspot**

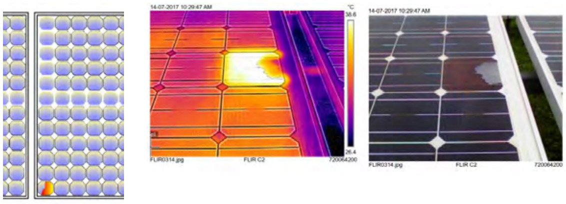
There could be bypass diode failure or uneven soiling. Or

PV cell failures: Hot spots can occur due to any severe failure or combination of different failures



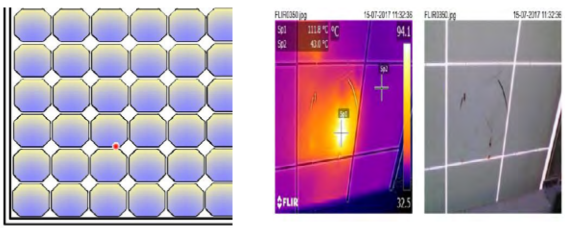
- **Partial hotspot cell/s.**

Bubbling effect on the rear side of the cell, active cell cracks



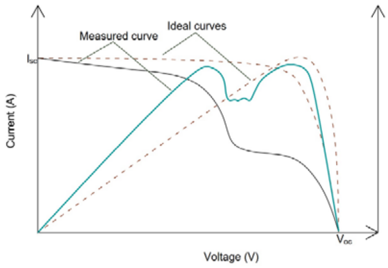
- **Pointed hotspot**

Interconnection ribbon failure or corrosion. Abnormal increase in temperature (~150^0C) i.e. 2 to 4 times the temperature of a normal cell.



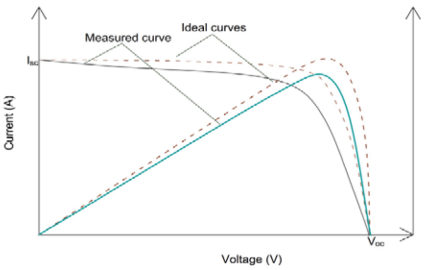
- **Stepped IV curve**

Stepped curve or notches in the I-V curve represents the mismatch effect. Mismatch can be due to many factors, like shading, non-uniform soiling, bypass diode failure, etc. Multiple maxima produced in the I-V curve will mislead the inverter's MPPT, thereby reducing its efficiency.



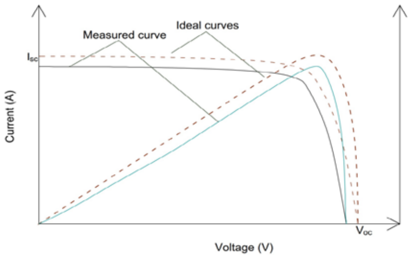
- **Low current**

This can be due to uniform soiling, thick shadow or hard soiling on the lower length edge cells of a PV module (will bypass the sub-string on module), aging or degradation of the PV module.



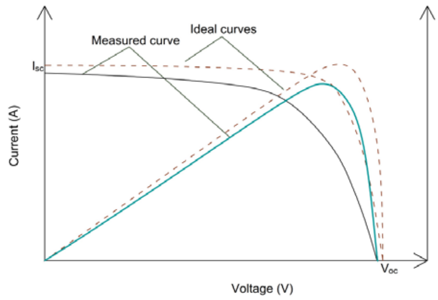
- **Low voltage**

This can be caused by conducting bypass diode, or the incorrect number of modules in PV string, potential induced degradation (PID), thick or dark shadow on the module which enables the bypass diode, or ground fault.



- **Rounder knee**

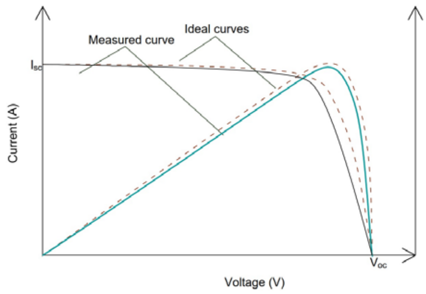
This can be due to ageing of the PV module, or due to change in series and shunt resistance (which will change the slope of the vertical and horizontal legs), or PV module failures.



- **Increased slope in vertical leg**

This may be caused by the increase in series resistance (R_s). Increase in series resistance is due to PV module faults/failures, fault in DC interconnection. Special attention needs to be given in this case, because an increase in series resistance can increase hotspots in wiring or connections which can lead to severe fire hazards. Perform IR imaging to identify hotspots.

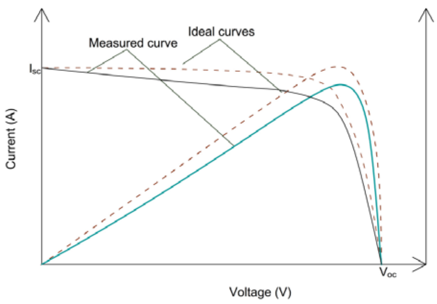
If the measurement is carried out on string with a long run cable, the series resistance may increase. In such cases, repeat the test after bypassing the long run cable.



- **Increased slope in horizontal leg**

This is due to shunt current paths in PV cells, module I_{sc} mismatch (in case string I-V curve tracing), or/and soiling and shading on PV module (Figure 6.29). Usually shunt current path can occur due to any localized defect in either cell or cell interconnects. This can lead to local hotspots.

The main reason for module I_{SC} mismatch in a string is due to manufacturing discrepancies or uneven degradation of PV modules. If the mismatch is small and randomly distributed across the string, steps or notches may not be present in I-V curve.



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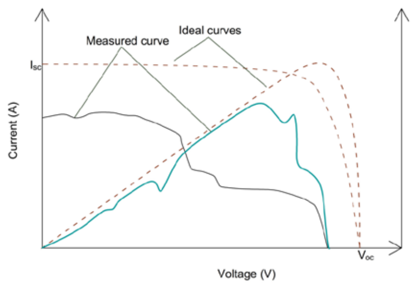
- **Fully distorted curve**

May be caused by the non-uniform shadow on string (tree shadow), or a combination of soiling, shadow and other causes of mismatch effect.



Sometimes incorrect information given to the I-V curve plotting software (changes in PV module rating or model, changes in array information like number of strings in series) may lead measurement error. Issues with I-V tracer irradiation sensor (calibration issues, short time variation in irradiance due to cloud change, the shadow on sensor, sensor misalignment, measuring at low irradiance) can also cast error on measurement.

SPARE PARTS MANAGEMENT

Spare parts management is an important tool which helps us to reduce the downtime of a solar power plant. By executing a perfect spare parts management system, an O&M company or contractor can control downtime by performing corrective maintenance in a timely manner. Generalizing spare parts management is difficult among solar power plants because of variations in:

- type and capacity of power plant.
- O&M contractual requirements: Downtime/uptime, response time, rectification time.
- spare parts storage location: Distance from the power plant, environmental conditions.

Addressing spare parts management in small or individual power plants is not a complex task. However, it was observed during the site analysis that there are certain factors to be addressed to proper spare parts management such as:

a) Technology advancement, b) Economics of spare parts, and c) Warranty

a) Technology advancement

The solar PV industry is one of the fastest changing sectors as new technologies and components are coming into the market rapidly. This technology advancement happening in all components associated with solar PV power plants such as:

(a) **PV technology**: A decade before maximum PV panel market share was holding by crystalline (especially mono) and Thin film technologies. But due to environmental consideration and due to increased production waste followed by reduced demand most of the thin film manufactures has obsolete from the market (Fraunhofer, 2019). **Figure 6** illustrates changes in PV market leading trends:

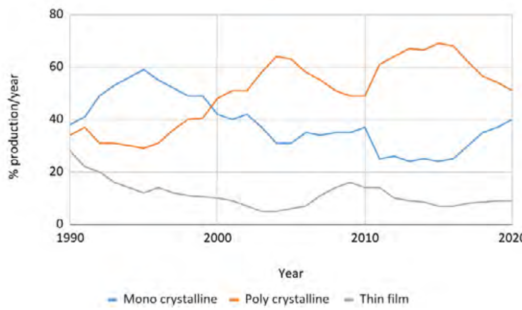


Figure 6: Technology wise PV panel production scenario

Last 10 years, poly crystalline silicon was leading the market due to low production cost, however, as per latest market study mono-crystalline silicon was at parity or had already taken over the leadership position of poly crystalline silicon in 2018 (Solar Power Europe, 2019). And it is expected that high efficiency thin film panels will improve its demand and production. Passivated Emitter Rear Contact (PERC) cell having 0.5-1% points efficiency improvements with little more cost of additional production equipment capturing PV market share exponentially. Compared to less than 1GW production of PERC cells in the year 2014, it reaches 60GW production globally in 2019. Also, there are drastic innovations going on in reducing BoM, by adapting 1500VDC systems, higher power rated modules (up to 450W+), bi-facial modules, glass to glass modules etc.

PV inverter: Inverter market adopting changes as per the market demands. The main changes like adoption of 1500VDC systems, PID resistance systems, improvements in efficiency, enhanced MPPT algorithms, etc. As the part of improving system energy yield now OEMs starts proving MPPT with optimizer as a separate system and inverter without MPPT, which enables module level monitoring and control with reduced cost.

Module mounting systems: For cutting down system capital cost, the current trend is to simplify module mounting structure (MMS). Improved tracking algorithms and its associated MMS are getting acceptance in the utility scale power plant market.

A smooth spare parts management should ensure zero downtime due to spare parts unavailability. It

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was observed from the industry that fast growing technologies have a direct relationship with spare parts management. This is because OEMs used to stop their manufacturing lineup once they decided to adopt new technology or materials for manufacturing. Any changes in manufacturing may impose difference in electrical parameters or the behavior of the equipment from the previous, even though that rated power is same. For example,

- If the voltage ratings of new PV panel are high: mismatch between one PV panels (new and existing) may affect entire string or strings connected to one MPPT
- If replaced an inverter's communication protocol is advanced: communication between other inverters will be difficult..
- If the new inverter is having a different MPPT voltage range: Alteration in existing string combination will be complex and expensive

During the site study it was found that power plant using thin film panels (especially glass to glass) faces spare parts deficiency since a large number of OEMs stopped manufacturing thin film panels. If the desired rated PV panels are not available, it was observed that asset owners either using one of the existing strings as spare or operating faulty PV panels. In both cases, asset owners are loosing generation due to reduced capacity in operation and mismatch losses respectively. **Figure 7** and **8** shows the amount of faulty PV panel found during the site survey.

Figure 7: Faulty PV panels in 7 years old utility scale power plant

Figure 8: Faulty PV panels in a 6 year old utility scale power plant

b) Economics of spare parts

In terms of financial feasibility, spare parts management is more feasible in large scale power plants, where even one hour down time will make significant financial loss. However by considering quantum of 40GW rooftop distributed power plants, even if the power loss due to spare parts issue not significant in individual power plant, losses on a macro level will be high. From the site observation on an average a 1MW utility scale power plant holding 10 additional PV panels. It was observed that small scale rooftop power plant owners holding 2 to 4 additional PV panels for 100kW. Which is only in the case of power plant installed under RESCO or OPEX model and asset owners holding more than 3 power plants in a locality.

c) Warranty

Since the solar power plant is an integration of a number of different components from multiple OEMs, warranty terms will vary. The general arrangement in warranty management can vary based on a plant's capacity and type of asset owner. Considering the financial feasibility, spare parts management and warranty management needs to be working hand in hand. This is because not all asset owners would be able to hold spare parts at site, in normal case they will claim for warranty or purchase replacements as and when it requires. As described earlier in this paper, due the market and technology change, OEMs may discontinue certain models. Tracking the manufactures market presents will help the asset owners to purchase enough spare parts before OEMs discontinuing certain models.

RECOMMENDATIONS

Solar PV power plants are going to play major role in India's total energy mix in future. Considering the expected total PV capacity of 100GW by the year 2022, any gap from the expected generation will affect demand generation ratio. Since the solar PV is a developing technology, dynamic changes in the market are unavoidable. For smooth running of the power plants which is under operation, it is desired to develop certain strategy to avoid asset management hurdles. This can be divided into two sections, steps to be followed before installation and after installation.

Step 1 :Before installation

Feasibility study: Along with all other technical parameter feasibility studies should consider expected O&M activities also. This includes access to PV plant, piping arrangement for cleaning, expected shadow and soiling at the site, etc.

Selection of materials: As per current practices, EPC or asset owners used to select materials which is best performing at the site. However, to avoid spare parts issues in future, it recommended to have technology due diligence for better market knowledge. Solar PV processionals or EPC contractors should have an updated knowledge on this topic. Technical analysis should cover at least 10 years expected market changes.

Along with this step, it is recommended to consider monitoring system accuracy class of the system as per IEC 61724 or equivalent.

Quality assurance plan: Most operational problems can be minimised by ensuring adequate material and workmanship quality, which can be done by adopting a Quality Assurance Plan (QAP). QAP documents should be prepared and discussed in detail before proceeding with installation. This will be used to verify plant handling over documents. QAP should contain

- *Data sheet, test certificate, warranty certificates of materials used in power plant*
- *Design methodology, specifications, SLDs, all GA drawings, layouts etc. (These documents should be updated version, in case of any changes during execution)*
- *Monitoring plan and methodology, Plant generation reporting methodology*
- *EHS plan during execution and operation including risk analysis*
- *Commissioning tests and documentation of initial performance*
- *Basic O&M plan , team and documentation strategies*

Step 2 :After installation/ Plant operation

Performance analysis: Monitoring of plant parameters followed by KPI verification will be the first step in performance analysis. Any significant observation should be followed by root cause analysis.

Documentation: It is desired to have proper documentation (preferably digital) of all activities along with generation details.

Spare parts management: A proper management can reduce plant downtime, this includes stoking required spares, updating spare parts logs, tracking the OEMs status. Also OEMs need to inform their customers about any changes in their manufacturing lineup.

Updating KPIs: It is recommended to update KPIs as per the plant degradation. For example, it is not recommended to follow fixed PR throughout 25 years. This is because plant degradation is already taken into account during the initial feasibility stage itself (yearly expected values). So updated PR will give us a better idea on the gap between actual and expected PR.

O&M team capacity building: A confident and knowledgeable O&M team will make the O&M activities more effective. A perfect human resource management should make sure that the employees working in that organization are satisfied and safe at work site. The solar PV industry is one of the fast changing sector, new technologies and components are coming into the market rapidly. Updating in PV technologies, manufacturing methods, power plant installation methods etc., to avoid existing known failures may introduce new failure in future.

NOMENCLATURE

AJB	= Array Junction Box
BoM	= Bill of Materials
CUF	= Capacity Utilization Factor
CEA	= Central Electricity Authority
IV	= Current- Voltage
DC	= Direct Current
EL	= Electroluminescence
EPC	= Engineering, Procurement and Construction
EHS	= Environment Health Safety
GW	= Gigawatt
IR	= Infrared
IEC	= International Electrotechnical Commission
KPI	= Key Performance Indicators
kW	= Kilo Watt
MPPT	= Maximum Power Point Tracking
MU	= Million Units
MNRE	= Ministry of New and Renewable Energy
MMS	= Module mounting structure
NSM	= National Solar Mission
O&M	= Operation and Maintenance
OEM	= Original Equipment manufacturer
PERC	= Passivated Emitter and Rear Cell
PR	= Performance Ratio
PV	= Photovoltaic
PID	= Potential Induced Degradation
QAP	= Quality Assurance Plan
SLD	= Single Line Diagram

ACKNOWLEDGEMENT

This paper has been used qualitative and qualitative data collected from solar power plants spread across

13 states in India. Total 112 power plants have been visited and studied the O&M procedure followed.

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URBAN INFRASTRUCTURE
& UTILITIES

LEVERAGING ADVANCED METERING INFRASTRUCTURE TO SAVE ENERGY

Rachel Gold[1]

[1]*American Council for an Energy-Efficient Economy*
Washington, DC, USA
rgold@aceee.org

ABSTRACT

Traditional utility meters collect monthly data in one-way information flows. In the past fifteen years, advanced metering infrastructure (AMI) has enabled two-way power and information flows, improving visibility into customer energy usage. These integrated networks of smart meters, communication networks, and data management systems can enable customer energy efficiency.

In the U.S, AMI now represents 55% of all meters. In India, the National Smart Grid Mission roadmap aims for AMI rollout in 100 percent of towns by 2025. In India, AMI offers opportunities to support system reliability, lower energy costs through streamlined operations, increase transparency to address power theft, and support renewable and electric vehicle deployment and integration. However, AMI can support demand side management as well. AMI can benefit customers by enabling time-varying rate design and usage feedback. Utilities can use this data to target offerings to the customers most likely to benefit from them, enable buildings to serve as grid assets instead of static load and support distribution system planning. However, our research reveals that most utilities are not utilizing this technology to its full potential.

This paper will examine evidence from smart grid rollouts to understand how and to what extent AMI deployments have led to energy savings through these use cases. This research will explore what barriers (regulatory, structural, data management, etc.) prevent utilities from leveraging AMI, and what solutions might look like. By analyzing ongoing pilots and programs, primarily in the United States, we will provide a set of recommendations to maximize energy savings from new AMI rollouts in India.

***Keywords— smart** grid, data access, advanced metering infrastructure, program targeting*

INTRODUCTION

The rise in availability of granular usage data through advanced metering infrastructure creates opportunities for an evolution in the role of electricity customers. With more granular information and relevant insights about their energy usage, customers can become active participants in lowering their own bills, improving their health, safety, and comfort, and providing value back to other participants on the grid. These data are a critical building block of a more active marketplace for demand-side resources, where customers, working with or through independent companies and utilities, support the integration of renewables and electric vehicles into the grid, foster reliability, and build resilience.

Advanced metering infrastructure includes three major components:

- Customer-side smart meters that collect electricity consumption data in 5-, 15-, 30-, or 60-minute intervals
- Communications networks to transmit interval consumption data from the meter to utility back offices
- A meter data management system (MDMS) to store and process the increased volume of data. MDMS also integrate meter data with information and control systems, including billing, customer information, outage management and distribution management systems (DOE 2016).

AMI has grown rapidly in the US and is now deployed for roughly half of all meters in the U.S. as shown in

Figure 1, with projections of reaching 90 million meters by 2020 (FERC 2018).

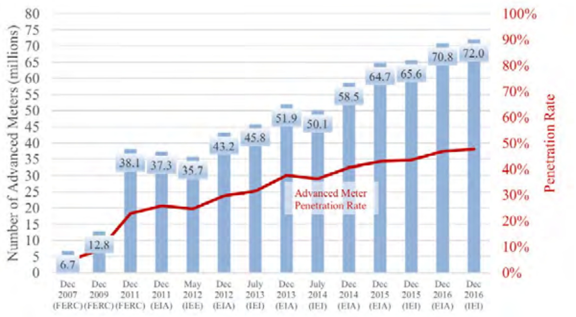

Figure 1: Advanced Meter Growth (2007-2016); FERC 2016

In India, EESL (Energy Efficiency Services Limited), a joint venture of state-owned enterprises operating as an energy services company, is working to replace 25 crore (250 million) convention meters with smart meters (Hindu Business Line 2019). This Smart Meter National Programme (SMNP) has deployed 5 lakh (500,000) smart meters as of August 2019, in Uttar Pradesh, Delhi, Haryana, Bihar and Andhra Pradesh. In addition, the National Smart Grid Mission (NSGM) supported deployment of 751,000 total smart meters as of September 2019 in Chanidgarh (two projects); Ranchi, Jharkand; Kochi, Kerala; and Rourkela, Odisha through grant funding (NSGM 2019).

Despite its potential value to save energy, most regulatory justification for smart meter rollout in the U.S. focuses on operational benefits to the system as a whole (DOE 2016). In India, SMNP cites billing efficiency and collection of DISCOM revenues as the primary value proposition for this effort, although they also mention the potential for customer feedback for better decisionmaking and control of energy in their homes. The cost of meters is recovered through energy savings from operational efficiencies (Hindu Business Line 2019). A review of the benefits highlighted in each of the five NSGM projects also finds a focus on operational benefits – reduction in Aggregate Technical and Commercial (AT&C) losses, improved billing efficiency. However, some of the projects mention potential benefits from reduced peak load, distributed generation and EV fast charger integration, and better consumer relationship management (NSGM 2019).

In this paper, we use evidence from the last decade of AMI deployment in the U.S. to understand the ways utilities, governments, and third party service providers are proactively using AMI data in support of customer energy efficiency and peak demand reduction. We characterize possible use cases for AMI and examine available evidence on energy savings. For promising use cases which are underexploited, we identify barriers to using these data in support of energy efficiency and discuss options to address those barriers from leading examples. We conclude by highlighting practices to consider in deployment and investment decisions in the U.S and India to ensure these data are used in support of customer energy efficiency.

METHODOLOGY

The primary goal of this research is to understand how utilities with AMI can better leverage its capabilities beyond purely operational benefits, to increase energy efficiency program effectiveness, influence customer behavior to reduce energy use, support more robust energy efficiency markets, and deliver system benefits through energy efficiency

To characterize the current landscape of how utilities are leveraging AMI, ACEEE conducted a survey of the top 52 electric utilities by sales in the U.S. We asked questions about the availability of AMI in their service territory and asked about their use of AMI in customer offerings and to support energy efficiency program design.

From this analysis we identifed potential use cases of AMI, then reviewed publicly available demand-side management program filings and interviewed utilities that had programs that leverage AMI capabilities. We also conducted structured interviews with program administrators to understand program details and what lessons learned and challenges they experienced.

POTENTIAL BENEFITS OF AMI FOR ENERGY SAVINGS

Typical benefits of AMI in utility business cases include a combination of operational or system benefits and customer-facing benefits. From our literature review and interviews, we identified four main operational benefits of AMI: reduced costs for metering and billing, reduced outage costs and fewer customer inconveniences, lower utility capital expenditures, and safety (DOE 2016). These align with the primary benefits cited by the SMNP and NSGM in India.

In addition, utility business cases for AMI often cite a range of customer benefits. First, customer-benefiting actions in aggregate can support system benefits. With AMI, utilities can give their customers the tools they need to reduce consumption and shift consumption from peak to off-peak times (NEEP 2017). These include pricing tools, like time-based rates and incentives, and informational tools, like customer bill alerts, online portals, and smartphone applications. Where customer usage is effectively reduced or shifted away from peak times, utilities can deliver system benefits through lower capital expenditures, avoided green house gas (GHG) emissions, and resultant customer bill savings (DOE 2016). Finally, utilities can better target energy efficiency programs to customers using AMI, better measure the results of those progams, and can better plan for and procure energy efficiency as a lower-cost resource on their systems.

DISCUSSION AND RESULT ANALYSIS

Use Cases

ACEEE surveyed the top 52 electric utilities by sales in the U.S. to understand how they are leveraging AMI in their programs. Where it was available, we captured which utilities had the following programs or program measures in their portfolios as of the most recent program year, 2018:

- Real time energy use feedback to customers
- Behavior-based programs that use AMI data for feedback and energy-saving tips
- Time-varying rates (including TOU, time-of-use rates)
- Smart, or grid-interactive efficient buildings
- Programs using data disaggregation from interval usage data to target and market programs to customers

Our survey results found 21 utilities that leverage AMI for 2-4 use cases. We also found 5 utilities reporting using AMI for only one use case and four that reported no use of AMI for these use cases. Utilities that have less than 5% AMI pentration were not included in this analysis.

Of the utilities with 5% or greater AMI penetration, behavior-based feedback and TOU rates were the most prevalent, with 24 and 26 utilities implementing these measures respectively. Behavior-based feedback, as described below, does not require AMI data but can use AMI data to enhance the customer experience. Similarly, while AMI may more readily enable implementation of TOU pricing, AMI is not required for TOU rates since the periods and pricing are fixed up-front. In contrast, AMI is required for more real-time forms of pricing. Real-time feedback was also a prevalent use cases, with 13 utilities leveraging AMI for this use case. 7 utilities use data disaggregation to target and market relevant programs to specific customers, and 4 utilities offer grid-interactive efficient building programs.

Our interviews reflected these trends. Most utilities that we interviewed have programs that provide customers with direct feedback, and many used AMI to support time-varying rates. Building on these results, our literature review and interviews with experts for the current study revealed six use cases by which AMI enables or supports energy savings, especially energy efficiency: 1) Direct feedback , 2) Pricing feedback through time-varying rates, 3) Targeting for program design, marketing, and technical assistance, 4) M&V 2.0, 5) Smart, or grid-interactive efficient buildings, and 6) Procurement and pay-for-performance

Two of the use cases are primarily driven by customer actions – "direct feedback" of interval usage insights through information provision and "pricing feedback" when customers respond to the more granular rates enabled by AMI. Utilities and third parties provide these informational, behavioral and pricing signals, but customers are the primary actors. Other use cases are behind-the-scenes enabling mechanisms for energy efficiency programs: targeting and improved EM&V are two ways that utilities and implementors can design more cost-effective, targeted programs. Other use cases focus on market animation and optimization of demand-side resources: using AMI data to enable procurement of those resources best positioned to meet system energy, capacity, and flexibility needs at least cost; and deployment of smart buildings that provide grid and customer value. Below, we characterize each use case and provide some examples.

Direct Feedback

AMI can provide customers more granular feedback on their energy use. Rather than a single monthly reading that gets reported to customers about a month later (a lag due to typical utility monthly billing cycles), customers can receive near real-time data on their energy use if coupled with a technology display on a phone, computer, or in-home.

While such more timely feedback can influence customer behavior and corresponding energy use, for most customers simply providing such data is insufficient to affect energy use. Buchanan et al. (2015) reviewed a large set of customer feedback studies and concluded that there is limited evidence that feedback alone is effective in getting customers to reduce energy use. Karlin et al. (2015), however, conclude that feedback is a promising strategy to promote energy conservation, but this depends on the how information is conveyed to customers and incentives to motivate them to take actions that affect their energy use. Sussman and Chikumbo (2016) find that most real-time feedback programs report net electricity savings in the 5-8% range using opt-in designs.

Program experience and studies of consumer behavior have shown that the best way to maximize the effectiveness of feedback is to provide it through an engaging medium, with incentives, normative reporting (comparisons to similar users) and specific, recommended actions (Sussman and Chikumbo 2016). Energy use feedback needs to be coupled with programs, services, and pricing that can motivate, assist, and reward customers for taking actions. In a pilot AMI program, CenterPoint Energy used a web portal to provide information on how to better manage their energy and peak usage, with prizes for successful responses. Participants reduced peak demand by an average of 5 percent during 10 events; some reduced consumption by as much as 35 percent (DOE 2016*).*

Mobile applications are another way to for utilities to provide feedback and can be an effective tool to engage customers. For example, Detroit Edison offers a mobile application, Powerley, that gives customers feedback and targeted energy usage insights based on their consumption patterns and allows customers to set goals. Customers can also request an Energy Bridge that uses AMI to collect one-minute energy usage information and give customers real-time energy usage feedback through the app (DTE 2018).

In addition, AMI allows information provision to be paired with billing alerts or dynamic price information. Billing alerts enable utilities to let customers know when they are nearing a higher bil than normal through text message or email. Evidence from one randomized field experiment of high bill alerts at Xcel Minnesota found 0.4-0.6% savings per customer (Fulleman *et al* 2019*)*. Behavioral demand response (BDR) strategies provide peak day notifications and post-event feedback to encourage reductions; these can be paired with peak time rebates or other pricing tools. Baltimore Gas & Electric delivered over 300 MW of savings each summer from 2015-2017 through a combined BDR and peak time rebate offering (AEE Institute 2019).

Pricing

Prices for electricity can vary widely due to system power demand and the different costs of production among electricity suppliers. Generally the highest prices for wholesale power occur during times of peak power demand. Historically, retail electricity rates for most customers do not reflect these dynamic prices.

Time-varying rates can better reflect the dynamic costs of electricity markets. Dozens of pilots across multiple countries provide compelling evidence that customers respond to changes in volumetric (kilowatt-hour) rates (Baatz 2017, Faruqui *et al*, 2017). Time-varying rates are increasing in popularity, with deployments at scale in Arizona, Oklahoma, and Ontario, and as the default option for investor-owned utilities in California.

An ACEEE review of 50 pricing studies (Baatz et al. 2017) found both average peak demand reduction and average reduction in overall consumption from a variety of AMI-enabled time-varying rates. Table 1 shows impacts from critical peak pricing (CPP), peak time rebates (PTR), and time-of use (TOU) rates, as well as combination of these methods. CPP and PTR use wholesale market prices to identify peak periods, and require AMI; TOU has pre-set periods so does not require AMI, although most utilities do not offer TOU without AMI. Of the 50 observations detailed in the table, 19 involved annual changes in overall consumption; the remaining 31 were seasonal.

Rate	# of Studies	Average peak demand reduction	Average consumption reduction overall
CPP	13	23%	2.8%
PTR	11	18%	2.3%
TOU	17	7%	1.2%
TOU+CPP	8	22%	2.1%
TOU PTR	1	18%	7.4%
All	50	16%	2.1%

Table 1: Reduction in overall consumption and peak demand for 50 treatment groups; Baatz (2017)

The table shows that time-varying pricing can be effective in changing customer use of electricity to optimize grid performance and yield cost savings to customers. The results also reveal that while TOU pricing does yield reductions in overall energy consumption (kWh), the biggest impacts are for peak demand (kW) reductions. In this way, TOU pricing functions primarily as a demand response strategy—a means to shape demand and create a more flexible grid.

However, some consumer advocates, regulators, and customers oppose implementation of time-varying rates, citing concerns about some customers' ability to respond to those rates. Sherwood *et al* (2016) highlights key design features that affect customer acceptance, including limiting peak period duration and critical peak pricing period frequency and coupling rates with technologies that automate customer response, such as programmable thermostats. Better notifications and shadow billing methods, which show potential savings before rate rollout, can also support customer acceptance.

Targeting

In addition to use cases for customers to directly manage their energy use using AMI data, utilities and governments with access to these data can also use this information to improve the effectiveness of energy efficiency programs. Energy efficiency targeting selects customers with particular characteristics as the focus of marketing efforts in order to increase savings and lower the cost to serve or recruit customers. Borgeson et al (2018) identifies three strategies for targeting:

- identifying whether a customer is able to participate (e.g, has the relevant end uses),
- whether a customer is likely to participate, and;
- whether a customer is likely to save more than others when the do participate.

Some strategies do not rely on AMI, instead using other forms of data - monthly usage data, demographic information, past program participation, and other characteristics – to target customers. However, interval data adds particular value to efforts to understand whether a customer can participate - for example, whether a customer has a pool and is therefore eligible for a residential pool pump program.

These data can also be used to understand whether a customer is likely to save more than others if they do participate. A targeting effort at Pacific Gas & Electric (PG&E) in California estimated the potential impact of targeting across a range of residential and small and medium business (SMB) programs. For whole-house retrofit and commercial direct install programs, they used non-AMI criteria, such as temperature-to-load correlation and total usage, to target the most promising half of customers, which they estimate would increase average participant savings increase by 53% and 76% (Scheer et al 2018).

Although program administrators can and should target some programs with monthly data feeds, interval data enables more precise targeting, and targeting schemes that rely on segmentation of usage, like discretionary kWh, baseload kWh, and kWh from cooling loads. For HVAC programs, the PG&E team found that targeting based on total usage was less effective than interval data that enabled researchers to isolate the portion of usage from cooling. HVAC program targeting could increase savings by eight times the average participant savings, although this was partially due to low, near-zero savings with average participants (Borgeson et al 2018). This method of targeting for program recruitment is currently being tested in the market with PG&E's Pay-for-Performance residential program.

Evaluation, Measurement & Verification

Targeting leverages insights from AMI data at the beginning of the program design process, to understand which customers to market programs to. Evaluation, measurement, and verification (EM&V) in energy efficiency occurs later in program development, to explore three objectives:

1. accountability: "Did the program or intervention deliver its estimated benefits?

2. risk management: "How certain are these savings?,"

3. continuous improvement: "What can be done to improve program performance in the future?

Chasta and Deshmukh (2017) highlight challenges from conventional M&V: inaccurate energy models, lack of transparency and confidence in the modeling results, inability to hand large data, and inability to incorporate real-time changes. AMI is one component of so-called "M&V 2.0" approaches, which aim to provide advanced data analytics and more real-time feedback to better meet accountability, risk, and continuous improvement objectives.

Chasta and Deshmukh (2017) note that AMI can be used to improve accountability by assessing peak demand reductions using estimates that vary based on time of day. These data can also increase the certainty

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of savings by providing more data points and relevant variables to improve the accuracy of energy models. Interval data can be used to separate large loads, like heating, cooling, and base loads that run continuously, and then used to better predict building performance.

Further, most EM&V happens after the end of a program year, delaying relevant insights for program designers. With AMI, program designers can get early, closer to real-time feedback, enabling enhanced program targeting, any needed adjustments to measure mix based on actual performance, and understanding the effectiveness of specific implementers and initiatives (Franconi et al 2017).

Where used proactively by utilities and evaluators, both more advanced and more real time analytics can improve the management, implementation, and design of energy efficiency programs. However, few utilities regularly leverage these data for accountability and continuous improvement. Franconi et al. (2017) notes that such analytics require good data quality and data access rules that enable utilities to share information internally and with evaluation contractors. However, the rise of pay-for-performance models described below may coincide with the use of M&V that leverages interval data where the program objectives relate to performance at different times of day.

Grid-Interactive Efficient Buildings

Stresses to the grid associated with peak demand, transmission and distribution (T&D) infrastructure constraints, and an increasing share of variable renewables create an opportunity to expand the role of flexible, controllable electricity loads to support reliability and lower system costs. Grid-interactive, or smart, buildings can serve this role by combining resources that deliver grid and customer value like demand response, storage, and energy efficiency.

To serve these multiple roles requires information and communications technologies -- interval data from either AMI or building automation systems, to understand the best ways to respond to grid needs, combined with controls for both the building and communications back to utility or aggregator offtakers of the building's services. These data and controls can be used in utility program offerings, or in projects implemented by with third-party aggregators and building owners. To date, there are limited examples of such integrated programs. In our survey, only four utilities of 52 said they are running integrated programs. These are primarily automated demand response programs that also offer energy efficiency audits or measures.

Procurement and Performance-Based Program Models

Pay for performance, an emerging model for energy efficiency program design, rewards energy savings on an ongoing basis as the savings occur, rather than providing up-front payments based on deemed or custom measure calculations. These programs are increasingly "meter-based" pay for performance (P4P) programs, which determine performance payments based on savings quantified using meter data, including daily, or hourly data from AMI where available (Best et. al., 2019).

Some of the benefits of meter-based P4P are not AMI-dependent. Meter-based P4P can increase investor and utility confidence that energy efficiency is a quantifiable, reliable resource, through the use of actual savings instead of engineering estimates. Meter-based P4P could also reduce oversight of program implementors by setting competitive procurement requirements and quality standards, and then letting implementors figure out how to best incentivize customer adoption. Finally, these program designs could reduce silos between programs, enabling integration within customer offerings by letting a broader range of technologies participate.

Currently, the meter-based P4P landscape includes some program administrators without AMI, like Energy Trust of Oregon. Others, like PG&E, Efficiency Vermont, and NYSERDA's collaboration with ConEdison, do leverage AMI. In interviews, these program administrators cite additional potential benefits from meter-based P4P with AMI: alignment with GHG reductions and grid needs and continuous improvement in program design.

With more granular interval data, program administrators can set performance payments that scale based on the value offered to the grid or to GHG reduction at different hours of the day or location. For example, ConEd could offer localized incentives in night-peaking areas of Brooklyn or mid-afternoon peaking areas of Manhattan on the same summer day. While utilities could use average load and savings shapes to value savings happening during system peaks, interval data offers a more granular, accurate understanding of the time-value of energy efficiency and localized impacts on the grid.

Interval data also allows for better modeling of energy consumption. With better models, evaluators, utility

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planners and investors can have more confidence in the savings, and program administrators and perhaps even policymakers can better forecast results before the end of program cycles in order to make key adjustments (e.g, to incentive levels) and support the program targeted described in the use case above.

Even those that do leverage AMI for some purposes may not use its full functionality at first. To reduce complexity, NYSERDA and ConEd do not yet offer additional incentives in performance payments for peak summer savings which would require AMI data, although they intend to do so in future project phases.

PRACTICES TO LEVERAGE AMI TO SAVE ENERGY

Actors across the energy ecosystem, from utilities to regulators, to third party companies and customers, all have a role to play in leveraging the resources from AMI in support of energy efficiency.

Leveraging AMI to save energy certainly requires active efforts from utilities in their roles as energy efficiency program administrators, grid planners and operators. They are also the primary entities identifying AMI technologies, selecting vendors, and investing in these resources on behalf of the system and their shareholders.

Utilities face numerous barriers toward implementation of AMI. The biggest challenge appears to be data management and system integration to enable each of the use cases described above. AMI produces much much higher volumes of data, which require new systems and processes, as well as new skills from the utility workforce or contracting with qualified vendors. Utilities will require complementary investments in billing, data management, and communications systems to realize the full spectrum of customer and grid benefits. AMI data also needs to be readily available to DSM program managers, system planners, and system operators – not just customer billing and records departments.

One key to successful roll-outs is customer engagement, which requires market research, customer targeting, and stakeholder and community outreach. Continued engagement efforts include providing customers with accessible support, education, and personalized energy usage insights.

Another key to gain the greatest benefits from AMI is to couple it with time-varying pricing. This provides the best opportunities for customers to reduce costs by modifying their energy use. Time-varying pricing is also critical for grid flexibility; it sends appropriate price signals to customers reflecting system costs at different times. Such signals enable customers to shape and shift load to optimize grid performance and reduce system costs.

Regulators and policymakers can have strong influence over utilities' ability and motivation to better leverage interval data in support of energy and peak demand savings. When they review initial proposals for smart meter deployment, they can ensure that proposals include and accurately quantify a full set of customer benefits, including saving energy and reducing costs. Once deployed, they can set AMI cost recovery contingent on delivery of benefits claimed in proposals, or can create performance incentives or other mechanisms to align spending with desired outcomes.

Regulators can also encourage needed complementary policies and investments, including time-varying pricing and data access rules that ensure data security and provide options for customers to use and share their data with third parties. They can also require or encourage pilots and innovation activities to test and scale 'applications' that leverage AMI data for customers, the market, or the utility.

Finally, the ecosystem of third parties can provide critical services to utilities or their customers that leverage AMI in data science, customer segmentation, customer marketing and program implementation. Of course, customers also have a key role to play, as many of the use cases for AMI to save energy require their initial investment or continued participation.

CONCLUSION

AMI is an important step to support a modern, flexible grid that can accommodate clean resources. The U.S. and India are ramping up AMI deployment, creating opportunities to use these interval data not just for operational benefits, like billing efficiency and collection of DISCOM revenues, but for energy savings, peak demand management, and integration of renewables and EVs. These data can be a critical tool to meet India's energy efficiency targets, including the Intended Nationally Determined Contribution commitment to reduce emissions intensity per unit GDP by 33 to 35 percent below 2005 levels by 2030 (UNFCC 2018).

We find that the energy savings possible through different uses of AMI to advance energy efficiency vary. Some have been well developed and documented; these include direct feedback, which ranges in savings from 1-8% depending on program design, and pricing feedback which can save 1-7% of kWh consumption, depending on rate design. Other uses of AMI to achieve or support energy efficiency are in development, newly emerging, or too dependent on specific applications to generalize potential energy savings; these include: 1) targeting customers for energy efficiency services and incentives, 2) advanced measurement and verification 3) grid-interactive efficient buildings, 4) pay-for-performance programs.

To achieve this result, however, takes more than simply providing customers with much more detailed, granular energy use data. To realize such benefits requires active customer engagement and a range of services and incentives that enable, motivate, and support customer action.

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FLEXIBILTY - THE KEY TO SURVIVAL IN THE UPCOMING ELECTRICITY GRID - A GERMAN EXPERIENCE

Dr. Wilhelm Josef Derichs[1]

[1]WJD Consulting
Bespoke Engineering, Tailored Solutions
52499 Baesweiler, Germany
willy@derichs.eu

ABSTRACT

Flexibility was the key factor which enabled RWE Power to maintain its position as one of the most important utility companies in Europe and to remain the second largest in Germany.

Some ten years ago the electricity market in Germany started to be influenced by renewable energy, first wind then solar. The initial slow uptake of renewables turned into a rapid growth and surprised the utility companies.

In order to survive in such an electricity market with an extremely fluctuating base load caused by first priority renewables RWE Power started an emergency program; its main purpose being to completely change the policy of the company from a mainly baseload to a middle load provider with a major input into stabilising a highly unsteady grid.To achieve this change the portofolio of the utility had to be altered and ways had to be found to create flexibility in all kinds of power stations, even in nuclear ones.

RWE Power is mainly known for its lignite fired power stations with some 20 boilers of around 10 000 MWel and for operating the associated mines. The original baseload designed power stations were retrofitted in a very short term into middle load ones with a much decreased minimum load and very high flexibilty. Nowadays the lignite boilers, operating as a pool, react to load changes in the grid with up to 5500 MW in 40 min, i.e. 140 MW/min. No gas turbine offers such a flexibility.

But it is not only the technical aspect which has to be outlined. As important is the change in mentality and self-understanding of the whole company and all its personnel from the top management down to shopfloors and operating rooms. The necessity for flexibility and lean managment went to the top of the agenda in workshops, seminars, leading fora. Even board games and computer games were developed to teach the impact of first priority renewables to the grid and as a consequence to our new business model.

This presentation introduces a personal overview of the important steps RWE Power went through to establish itself as a major player in the European electricity grid.

Flexibility, Renewable Energy, volatile base load, policy change, technical and mental retrofit, EEG-Bill, Germany

INTRODUCTION

India is, as a rapidly developing country, facing a tremendous change in its electricity market. Its demand for electricity is rapidly increasing and a large proportion of it is planned to be provided by renewables, mostly wind and solar. These will, with their typical volatile character, influence the stability of the electricity grid and thus the operation of the conventional fired powerplants.

The situation India`s electricity economy is facing happened to Germany a decade ago. The initial slow development of renewables suddenly turned to rapid growth and was of considerable threat to the existing utility companies and their portfolios. In Germany, by law, renewables have first priority in the electricity grid, i.e. the classical baseload providers have lost their position in the merit order. With its lignite fired utilities and the nuclear ones RWE Power, second biggest utility company in Germany, was one of the baseload providers and thus had to find measures to survive.

THE RENEWABLES BILL AND ITS CONSEQUENCES

In 2000 Germany introduced a bill to promote the development of renewable energy for the production of electricity (BmWi, EEG, 2019).

Its main mechanisms were

- to oblige the power suppliers to accept any electricity generated by renewable energy into the grid and
- to guarantee a fixed price for 20 years, being subsidized by a floating fee payed by the customers.

As a result of this bill the installation of wind turbines increased. But at first investors were hesitant and photovoltaics were too expensive. Thus the portion of renewables in electricity production increased only moderately and had no significant impact on the operation of the classic power stations.

This changed dramatically in the years 2008/2009 due to a sharp drop (25%) in installation costs for photovoltaic plants; a cost decrease which continued in the following years and made investments in renewables highly attractive. The installation, especially of photovoltaics, increased rapidly, see Figure 1, and thus the electricity produced by renewables.

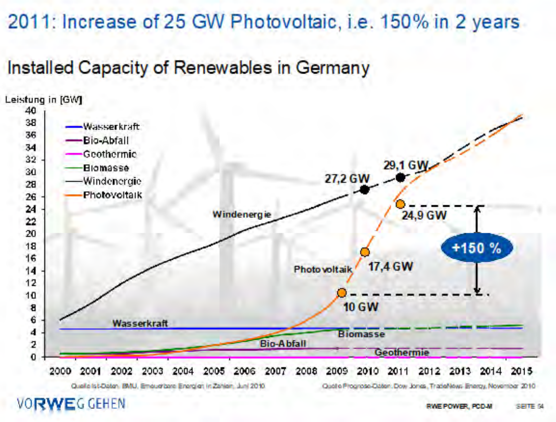

Figure 1, Increase of Renewables

In just two years gas turbines lost their typical daily run around the noon peak as now photovoltaic was taking over. Gasturbines were not operating anymore from one year to the other, see Figure 2. Most of them were mothballed. Note: Nowadays gasturbines are experiencing a revival, due to increasing costs for CO2-emissions.

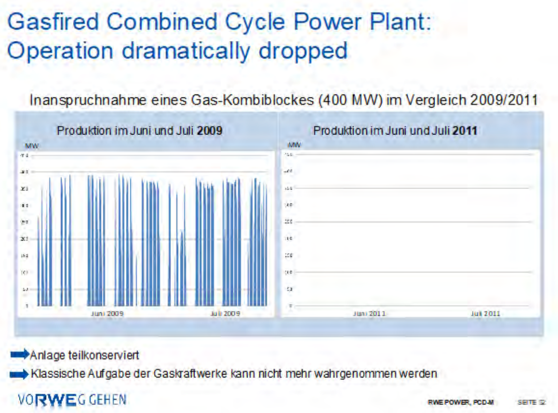

Figure 2, Operation of a gas fired unit

At the same time classic baseload providers lost their position in the merit order, were pushed back and had to operate more flexibly due to the volatility of wind and solar, see Figure 3 and Figure 4.

The lignite fired boilers of RWE Power were not designed for such flexibility, with rapid load changes, low but still efficient minimum load, short stops, fast startups, etc. Often they could not be operated economically. Energy having been sold years before on longterm helped to keep the portfolio balanced.

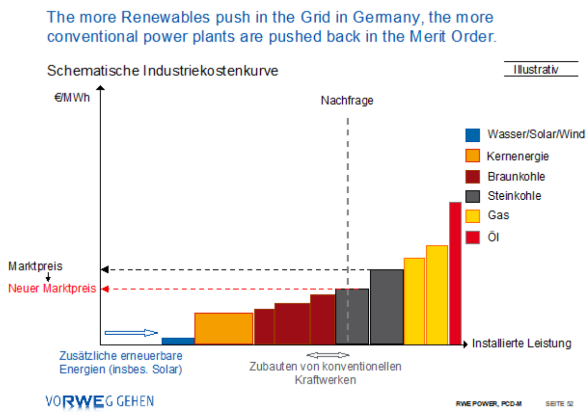

Figure 3, New Position in the Merit Order

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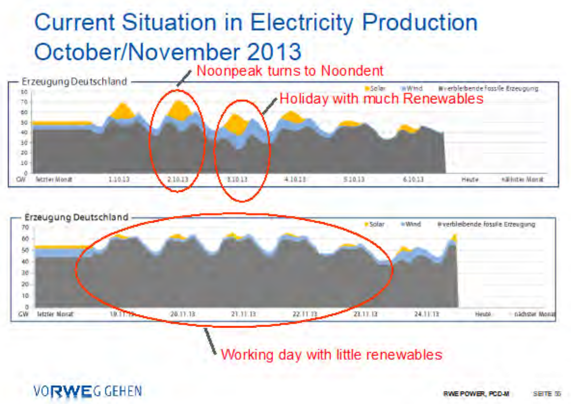

Figure 4, Load Sequence Operation

THE NEW POLICY

In this emergency the company, from the board to the shopfloors and operating rooms, restructured itself from a slow steady conservative baseload provider with records, documented in the Guiness Book of Records, for the longest running operation without outage into a high class middleload provider with high flexibility and considerable potential to stabilise the grid. This endeavour involved major technical measures as well as the human factor and had to be accomplished in a narrow time window.

Technical Measures:

1. **Minor faults and return to designed specifation**

   The technical measures started with a close look at the utilities and not only at the planned repairs or faults known and listed to be done at the next outage or revision. A thorough review with the operating team was undertaken to find the source of the "character" of each unit (boiler, turbine, fluegas desulpurisation and other components). Any deviation from the original design specification was investigated. Often enough sources for peculiarities were found to be minor faults like slightly incorrect position indicators, small irregularities in water/steam distribution in the boiler, incorrect distribution of fuel and/or combustion air, uneven steam flow to the turbine, etc. All the small irregularities were not important by themselves but added together were leading to e.g. less maximum or minimum load and lower load gradients, pressure oscillations in the fluegas in the combustion chamber at certain loads.

   In brief, the first step was to get the units of the powerplants back to the designed specification.

2. **Limits, thresholds, boundary values**

   Thresholds, limits and boundary values dated mainly from the time of the commissioning, were often determined more than 30 years ago and in a very conservative manner. Ventilation time, holding points, single process steps etc. were reviewed. Temperature gradients of major thick walled components were recalculated in updated mathematical models. Process steps in startup procedures were parallelized as much as possible. While assuring that the measures were not affecting plant lifetime and most certainly not plant safety, start up and shut down times could be remarkably reduced from 9 hours to less than 4 hours, see Figure 5, and load changing rates already increased. More than 70000 l of oil were saved per cold startup.

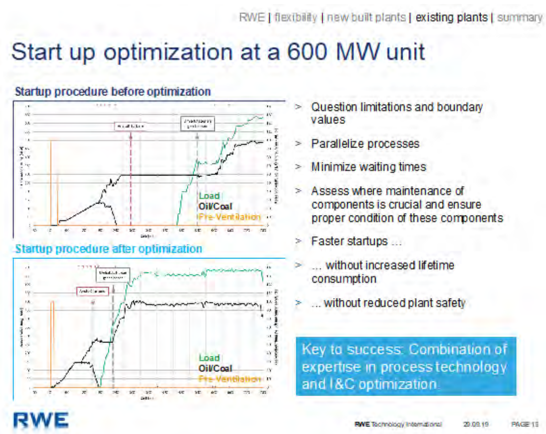

Figure 5, Start up Optimisation

3. **Major Components**

   At regular maintenance and/or revisions it was economically evaluated whether to retrofit major components like turbines with enhanced blade shape for higher efficiency and thus more load, optimised cooling systems in the cooling tower, condenser with improved internals to increase the droplet surface, combustion optimisation by adjusted combustion air and pulverised lignite, overhauling the header to reduce stress caused by inappropiate shape, components for condensate build up, throttling of superheated steam, application of chrome-nickel based alloys in pipes for superheated steam, see Figure 6.

4. **Instrumentation and Control Pooling**

   Each unit had its own control room and instrumentation and control (I&C) equipment dating from the seventies and was operated independently from the neighboring unit.

   By retrofitting the units with modern I&C-equipment the operation of the units could be facilitated, the automatation increased, the control performance and quality improved, the communication between the units was enhanced, units were pooled and operated from one control room. Finally all the units of the power stations of the lignite division were virtually pooled and operated as an entity.

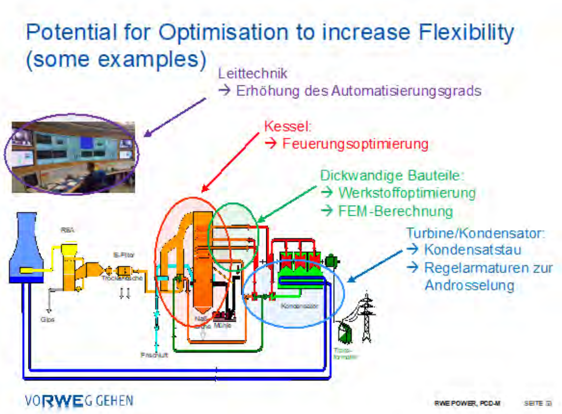

Figure 6, Potential to increase Flexibility

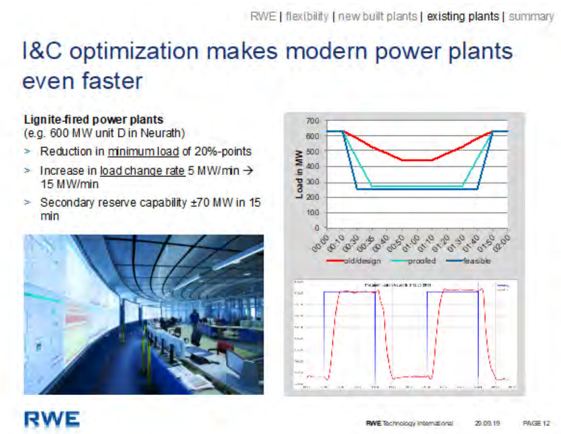

Figure 7, Improved Flexibility at 600 MW-Unit

5. IT-Diagnosis- and Prognosis-Tools

IT-Diagnosis- and Prognosis-Tools were installed to evaluate the data now easily accessible due to the new I&C. Hence, constantly updated information about the status of the single units and the pool concerning temporary disposible load (maximum / minimum), viable load changing rates and the potential for secondary control capacity became available. Thus the company developed into a player in the dayahead and intraday electricity market to gain extra profit at peak (positive as well as negative) electricity prices.

In all, in less than three years, more than 220 million euro were invested in state of the art equipement with the result that minimum load could be reduced, load changing rates were improved and secondary control capacity could be offered, e.g. for a 600 MW-unit: 420 MW to 230 MW, 5 MW/min to 15 MW/min, 60 MW at temporary overload operation by closing bled steam for feedwater preheating and holding up the condensate.

The lignite units of about 10,000 MW capacity are finally capable of responding to load changes in the grid as a pool with +/- 5500 MW in 40 min, i.e. 140 MW/min, permanently and in case of minimum load with another - 2600 MW for about 4h in turbine bypass operation.

Human Factor:

With all the technical measures implemented the main factor behind the successful transition of the company is the human resource.

Traditionally, the entire personnel of RWE Power were trained for decades to successfully operate the units at full capacity in baseload. The new demands called for complete rethinking and a new mentality.

The board and the top management had been prepared to introduce a programme of lean management and continuous improvement processes. But the rapidity of the changes in the electricity market surprised us.

The board and top management were invited to forums to analyse the situation, detect the dangers and challenges and develop first strategies. The results were discussed as top down ideas in the divisions and the power stations, then in workshops with the personnel on the shop floors and the control rooms. Their input went back as bottom up ideas to the upper management levels and vice versa in an amplifying loop to develop the best strategies. In all steps the representatives of the trade unions were closely involved.

A training p-rogramme was initiated for the entire personnel from top to bottom, from technical to administrative, to understand the complex market and the neccesity to introduce a completely new policy.

Card board games with changing market scenarios during the game (classical, then without nuclear, finally with wind and solar) were developed, to teach the background of the merit order and the different focus to run its portofolio of powerstations, which the players received at the beginning of the game. The game was played in guided workshops with assistants who explained at the beginning the essentials of the German electricity market.

More complex and going more into the details of the dayahead and intraday of the electricty market were two-day seminars with presentations which led to a competion of the participants in a virtual electricity market computer game.

In small teams strategies were developed to create transparency of the economic situation for the personnel. The most successful idea was to inform the personnel about the chronological progression of the economic availability of the units, the power stations and the divison. The economic availability was the planned economic asset versus the actual economic asset, showing which power station is in positive or negative range, i.e. is making money or not. Flat screens at key points like the gate, the canteen, the office building, the control room etc. informed the personnel about the daily development.

Sensibilty to the market was addressed in every morning report and “8:30”-meeting by announcing the base and the peak price and the weather conditions, i.e. what was to be expected by wind and solar, and how the power station planned to operate.

In less than two years the majority of the personnel were successfully trained and were sensitive to the new situation of RWE Power in the electricity market. With such a new mentality the personnel applied the potential of the retrofitted units and gained substantial profit from the opportunities of the volatility of the market.

Figure 8, Human Factor

CONCLUSION

RWE Power overcame the challenges presented by the unexpected dramatic increase of renewable energy in 2008/2009 in Germany. Due to the EEG-bill from 2000 renewable energy had and has first priority in the electricty grid and is pushing the classic baseload providers into middleload ranges and the gas turbines out of the merit order.

In this economically dangerous situation RWE Power immediately started an emergency programme, including a technical and human retrofit of utilities and crews, who for decades were specialists in baseload operation. The target was to transform into a highly flexible middleload provider with a high potential for grid stabilisation, thus becoming an essential partner in securing the energy transition process to renewable energy.

A thorough review of the units, its boundary values, its single process steps and a technical retrofit reduced the cold start up time from 9 hours to just 4 hours, increased the maximum load and reduced the minimum load (e.g. 600 MW unit: from 420 MW to 230 MW) as well as improving the load changing rate from 5 MW/min to 15 MW/min.

The retrofit, with modern instrumentation and control, facilitated the operation of the units and data collection enabling the pooling of the units of the lignite division. Thus the lignite division could react as an entity to the demands of the Transmission System Operator (TSO) always having appropriate, constantly updated data of the pooled units concerning currently available maximum/minimum load, possible load changing rates and the amount of secondary control capacity. As a pool of about 10000 MW capacity the lignite division was able to respond to load changes in the grid with +/- 5500 MW in 40 min, i.e. 140 MW/min, permanently and in case of minimum load with another - 2600 MW for about 4h in turbine bypass operation.

But indispensable to the final success were the highly motivated people of the company. The main ideas were developed in workshops all over the different departments. The entire personnel were directly involved as a first priority, and were trained in the specifics and opportunities of the new electricity market.

The economic availabilty of single units, the power stations and the divison were presented on flat screens at key points like the gate, the canteen, the shop floors, the control room, the administration building etc. The economic availabilty being the planned asset versus the actual asset showed to everybody if we were in positive or negative range, i.e. making money or not. A new mentality with the feeling for the responsibilty of the individual was born.

These important and tremendous steps RWE Power, Germany´s second largest utility company went through finally resurrected the company as a successful big player in the European electricity grid and turned it into a crucial partner in the German energy transition process to renewables.

ACKNOWLEDGEMENT

Without the assistance of my former collegues at RWE Power this paper could not have been finished. I would like to acknowledge them for being partners in the discussion, for their constructive criticism, for valuable suggestions and for providing figures and background information. Finally there is Joseph Martin, an Irish friend, to thank for proofreading the paper and helping it to an acessible style.

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EMPIRICAL ASSESSMENT OF THE APPLIANCE-LEVEL LOAD SHAPE AND DEMAND RESPONSE POTENTIAL IN INDIA

Nihan Karali[1], Nikit Abhyankar[2], Aditya Khandekar[3]

[1]*International Energy Analysis Department*
Lawrence Berkeley National Laboratory
Berkeley, California, USA
NKarali@lbl.gov

[2]*International Energy Analysis Department*
Lawrence Berkeley National Laboratory
Berkeley, California, USA
NAbhyankar@lbl.gov

[3]*International Energy Analysis Department*
Lawrence Berkeley National Laboratory
Berkeley, California, USA
akhandekar@lbl.gov

ABSTRACT

Over the next 15 years, electricity demand from the key residential and commercial appliances is projected to be nearly 300 GW or ~65% of India's total peak demand. The objective of this study is to characterize appliance level demand and temporal variation, and identify the overall DR potential in India. We use Bangalore Electricity Supply Company territory (peak load of 3,505 MW in 2016) as a case study, using actual one-minute resolution load data for 2,979 distribution feeders and a detailed load survey. Our results show that agricultural pumping and space cooling (residential, commercial, and industrial) are the main contributors to the peak demand – with shares of 23-27% and 14-23%, respectively. Both sectors have about 1,000 MW of DR potential – agricultural pumps offering load shifting service while space cooling offering shimmy service that is capable of dynamically adjusting to react to short-run ramps and grid disturbances. Residential electric water heaters contribute nearly 18% of the winter morning peak demand and can also offer about 500 MW in shimmy service. Overall, we find that shifting and shimmy services offer 1,199 MW and 1,511 MW total DR potential, respectively.

Keywords—electricity, electricity demand, load forecasting, load modeling, demand response

INTRODUCTION

Over the next 15 years, electricity demand from the key residential and commercial appliances is projected to be nearly 300 GW or ~65% of India's total peak demand (Abhyankar et al., 2013; CEA, 2016). This is equivalent to the output of nearly 600 large power plants.

The objective of this study is to characterize end-use level demand and temporal (seasonal/hourly) variation, and identify the overall demand response (DR) potential in India. Up to now, only a few studies look at the temporal variations in end-use load and their DR potential in India. These studies are mostly based on load surveys and lack empirical load data. For example, Garg et al. (2010) characterize the demand in the city of Gujarat, based on load surveys. Similarly, Energy Efficiency Services Limited (EESL) presents system demand charts based on a number of representative feeders and load surveys conducted for Bangalore Electricity Supply Company (BESCOM) (PWC, 2015). Chunekar et al. (2016) analyzed the load shapes of typical household appliances in India. None of these studies examines system-level load issues, provides detailed bottom-up analysis, or estimates appliance DR potential.

We analyze the BESCOM territory, which serves the city of Bangalore and the surrounding area, as a case study.

BESCOM TERRITORY

BESCOM is an electricity distribution company serving eight districts of the state of Karnataka, which covered 8.8 million customers in 2016. It has four operating zones: Bangalore Metropolitan Area Zones - North and South (which we combine into one zone abbreviated BGM), Bangalore Rural Area Zone (BGR), and the other rural areas, Chitradurga Zone (TMK). Bangalore and surrounding area have a tropical climate with distinct wet and dry seasons. The coolest month is January (typically range from 16°C to 27°C), and the hottest month is April (typically range from 23°C to 34°C) (Weatherspark, 2019). The monsoon season, which runs from June through September, brings frequent rainfall that moderates the summer heat. November, December and January are considered winter months, while April and May are considered summer months. February, March, and October are the transition months, when the temperatures has an increasing/decreasing trend entering the summer and winter.

About 53% of BESCOM customers are urban and 47% are rural. Among those, 67% are residential, 9% are low-tension (LT) commercial, e.g., small offices, grocery stores, and shops, and 9% are agricultural (**Table 1**). Most agricultural customers are rural, most commercial customers urban, and industrial customers—including industries such as steel, copper, aluminum, food processing, plastic molding, and packaging—were evenly distributed between urban and rural areas.

Table 1: BESCOM Customers by Sector (2016)

	NUMBER ('000)	SHARE (%)
Total	8,798	
Residential	5,926	67.4%
LT commercial	782	8.9%
HT commercial	5	0.1%
HT industrial	7	0.1%
LT industrial	160	1.8%
Agricultural	824	9.4%
Others*	1,094	12.4%

* Others include municipal water pumping and supply, street lighting, and advertising boards. Note: LT = low tension that has less than 1 kV voltage, HT = high tension that has more than 1 kV voltage. Customers like individual houses, small offices, shops, and small manufacturing units are on LT lines, while HT is applicable to large industries and large commercial units such as information technology offices, malls, hospitals, and universities.

Figure 1 shows each sector's share in total BESCOM electricity sales in 2016. Agriculture consumed the most (27%), although it only receives electricity from 22:00 to 06:00 the next day to prevent power outages when system demand is higher. The next-largest consumers were residential (19%) and HT industrial (18%). The entire commercial sector, including LT and HT, accounted for about 25%, while LT industrial and others constituted smaller shares.

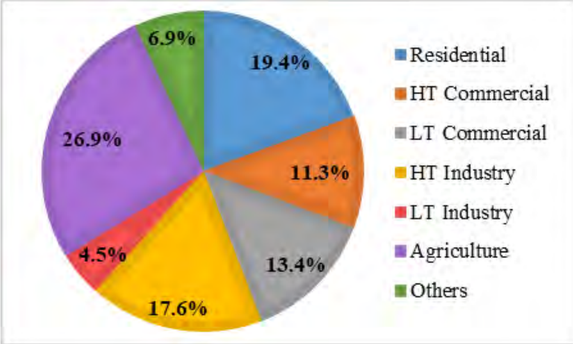

Figure 1: BESCOM Electricity Sales by Sector (2016)

DATA AND METHODS

Three primary data sets used in this analysis are as follows.

1. One-minute temporal resolution actual load data for the entire year of 2016 for every 11kV distribution feeder in the BESCOM territory (2,979 feeders in total). This data has operating zone details and was supplied by BESCOM.
2. Feeder-level consumer characteristics such as number of consumers in each sector category and zone broken down by electricity tariff slabs, average revenue in each month, and so on. This data was supplied by BESCOM.
3. A load survey performed by PWC / EESL in BESCOM's service territory to identify the penetration rates of certain key appliances and temporal profiles for various end-uses in the residential, commercial, agricultural, and industrial sectors (PWC, 2015). This data was supplied by BESCOM and EESL.

The analysis structure is shown in **Figure 2**. In step 1, we used programming languages Python and R to organize and clean the load data to create 15-minute averages for each of the 2,979 feeders. This feeder level load data is used in Lawrence Berkeley National Laboratory (LBNL)'s S-LOAD model that utilizes the feeder level consumer characteristics (described in #2 above) and the load survey data (described in #3 above) to decompose the total feeder load into various end-uses / appliances. In order to be computationally more efficient, S-LOAD decomposes the feeder load by sampling the most important feeders in terms of overall energy consumption. In Step 2, we used the consumer characteristics and load survey data from ~300 feeders (288 feeders to be exact in this study) covering over 30% of total annual energy consumption in BESCOM; 36 feeders were dedicated to residential areas / apartment complexes, 58 feeders were dedicated to industrial establishments (sum of

HT and LT), 31 dedicated to large commercial consumers like malls or large office buildings, 97 dedicated to agricultural consumers, 19 dedicated to other consumers, while 47 were mixed feeders for residential and small commercial or industrial consumers. S-LOAD can distinguish seasonal variations in daily/hourly load profiles to account for differences in human and economic activity. In Step 3, we use the month January to represent winter and April to represent summer. This is also consistent with the data presentation in PWC (2015). The appliance level load on each feeder is then used to assess the overall DR potential (Step 4).

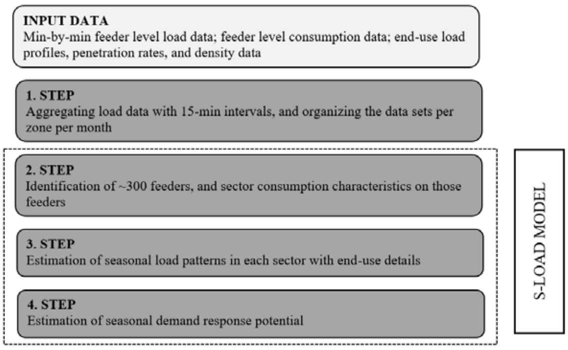

Figure 2: Summary of the Methodology

The model uses the annual 15-minute system load with operating zone detail to calculate the average daily load curves for each month with a 24-hour period. Next, the model creates the sector-level load profiles per momth based on the top 288 feeders. The remaining load calculated as the difference between the average daily load of a month and the sum of all sectors' loads in that month is labeled "Other". Each sector load is then decomposed to analyze the end-use details. In this analysis, S-LOAD uses load patterns (i.e., for a 24-hour period), appliance penetration, and appliance density (i.e., number of appliances per household or commercial unit) data from PWC (2015) for most appliances. For sectors that have no appliance (or end-use) penetration and/or hourly load pattern information, load characteristics from other cities are used, such as Garg et al. (2010). End-use decomposition of load curves is calculated as follows:

*End-use load (MW) = Average end-use load during the day (MW) * Load profiles* (1)

*Average end-use load during the day (MW) = Maximum possible end-use load during the day (MW) * Seasonal coincidence factor* (2)

*Maximum possible end-use load during the day (MW) = Total stock of end-use (million units) * Power consumption of end-use (W)* (3)

*Total stock of end-use (million units) = Total number of customers in sector i * end-use penetration * average density* (4)

In the final step, S-LOAD's DR potential module calculates the maximum DR potential of certain end-uses in each sector.

The sectors and end-uses included in this study are based on the BESCOM customer profiles and the end-uses provided in PWC (2015) survey.

Table 2 summarizes the unit power consumption levels, appliance penetration, and density levels used for the residential and LT commercial sectors in this study. Please see Karali et al. (2019) for the residential and LT commercial load profiles used in the analysis.

Table 2: Residential and LT Commercial Appliance Characteristics

		UEC	PENETRATION-DENSITY
Residential	Fan	70	94%-2.1
	Tube lights	60	75%-2.4
	Incandescent bulb	60	41%-2.2
	CFL	20	61%-2.9
	Electric water heaters	2,000	19%-1.1
	Refrigerator	55	48%-1.0
	Air conditioner	1,415	2%-2.0
	Television	80	80%-1.0
	Standby power	3	100%-1.0
LT Commercial	Fan	90	66%-1.8
	Tube lights	60	95%-3.6
	Incandescent bulb	60	20%-2.9
	CFL	20	42%-4.4
	Electric water heaters	2,000	2%-1.0
	Refrigerator	65	26%-1.1
	Air conditioner	1,415	3%-5.0

Note: UEC is unit energy consumption in Watts. Source: PWC (2015) and Abhyankar et al. (2017).

For the industrial sector, based on stakeholder consultations, we assume the end-use shares presented in PWC (2015)—5% pumps, 41% motors, 38% air conditioning, 10% thermal fluids, 6% others—of total daily industrial load are constant during the day across the LT and HT industrial sectors. On the other hand,

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the 100 industry customers surveyed by PWC (2015) include five information technology (IT) operations and two hotels that were on the industry-dedicated feeder. Thus, the real shares of industrial load from electrical equipment, particularly air conditioners, could be different.

In addition, because no directly relevant end-use information for HT commercial sector under BESCOM territory is provided by PWC (2015) or any other source, we base estimates for this sector on an analysis of commercial end-use loads from the state of Gujarat (Garg et al., 2010) after adjusting for the seasonal weather differences between Gujarat and Karnataka. Please see Karali et al. (2019) for the end-use shares that we used for HT commercial sector. Finally, because about 90% of Bangalore's agricultural load comes from irrigation, we treat the agricultural sector's load as one large end-use. For all sectors, we did modify the load shapes and shares based on inputs from BESCOM experts. In addition, because we analyze the region's entire stock of end-uses—hundreds of thousands of units of each—we do not consider load intermittency to be an issue.

DISCUSSION AND RESULT ANALYSIS

Figure 3 displays 15-minute load data aggregated at each of the three zones within BESCOM – BGM, BGR, and TMK. BESCOM's peak load in 2016 was about 3,505 MW, occurring on March 7 at 10:15 in the morning. The rural BGR and TMK zones peaked on March 2, while the urban BGM zone peaked on November 16. BESCOM's 2016 load factor is 0.7.

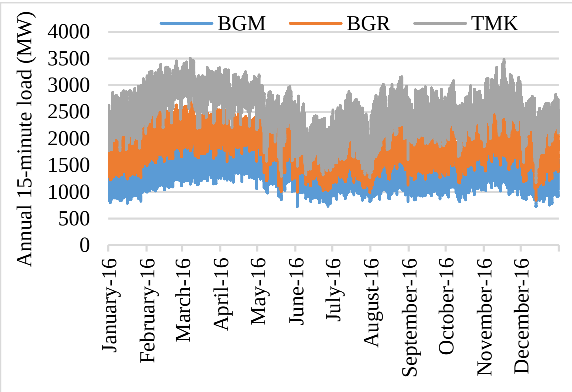

Figure 3: BESCOM 15-minute load in 2016 with operating zone detail

Figure 4 shows the BESCOM-wide 15-minute load curves, averaged for each month of 2016. Electricity demand is higher in February, March, and April. Summer peaks occur late in the morning (e.g., 08:00–10:00) and late in the evening (e.g., around 20:00-22:00). Electricity demand declines quickly in May. With the start of the monsoon season, June and July have the lowest electricity demand during most of hours of the day.

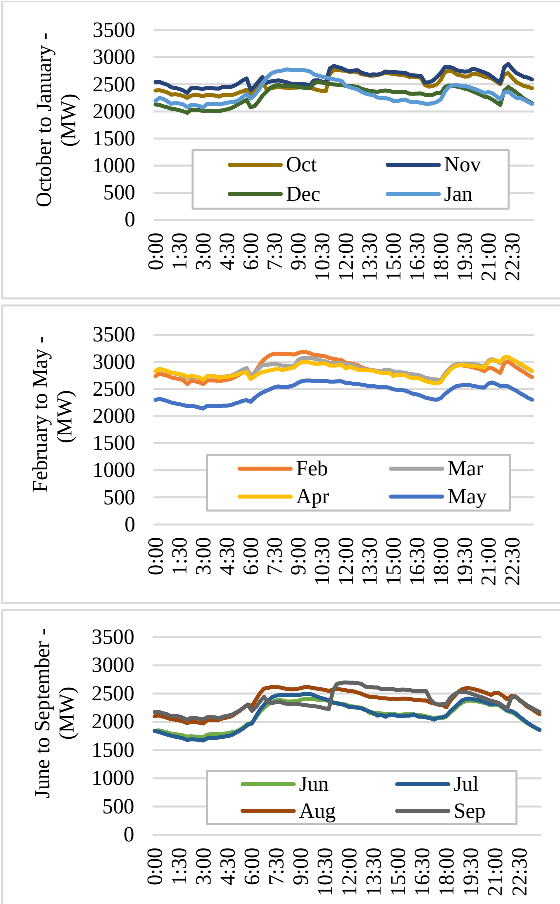

Figure 4: BESCOM-wide 15-minute average load curves for each month in 2016

BESCOM's average peak demand is estimated as 2,775 MW in winter and 3,090 MW in summer 2016 (**Figure 5**). Agricultural and residential demands decrease during the day, while LT commercial demand rises. Demands from the industrial sector (both LT and HT) and HT commercial sector are relatively constant, with some declines between 20:00 and 09:00 the next day. The two peaks in winter—with the morning peak higher than the evening peak—align with the residential load pattern.

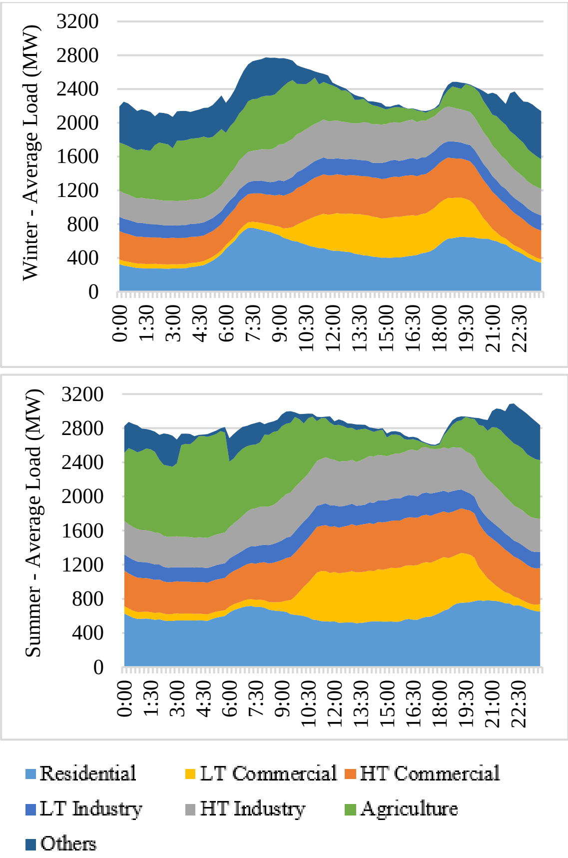

Figure 5: Average load curves with sector details

Residential Sector

As shown in **Figure 6**, BESCOM's average residential peak demand is estimated as 757 MW in winter and 784 MW in summer. The peak occurs in the morning in winter and in the evening in summer. Electric water heating accounts for almost 65% of the morning peak in winter and 56% in summer, even though the penetration of this appliance is assumed 19% with 1.1 density. Increasing demand for cooling is the reason for drop in hot water demand in summer mornings. In contrast, the evening peaks are mainly driven by lighting across the seasons (winter–55% and summer–40%). Cooling demand (both fans and air conditioners) accounts for 15% of the evening peak in winter and 27% in summer.

HT Commercial sector

BESCOM's demand from the HT commercial sector peaks around 10:30 and remains relatively constant until around 19:30, with minor variations in summer and winter (**Figures 7**). Average peak demand for this sector is estimated as 478 MW in winter and 561 MW in summer. The peak occurs during the evening in winter and late afternoon in summer.

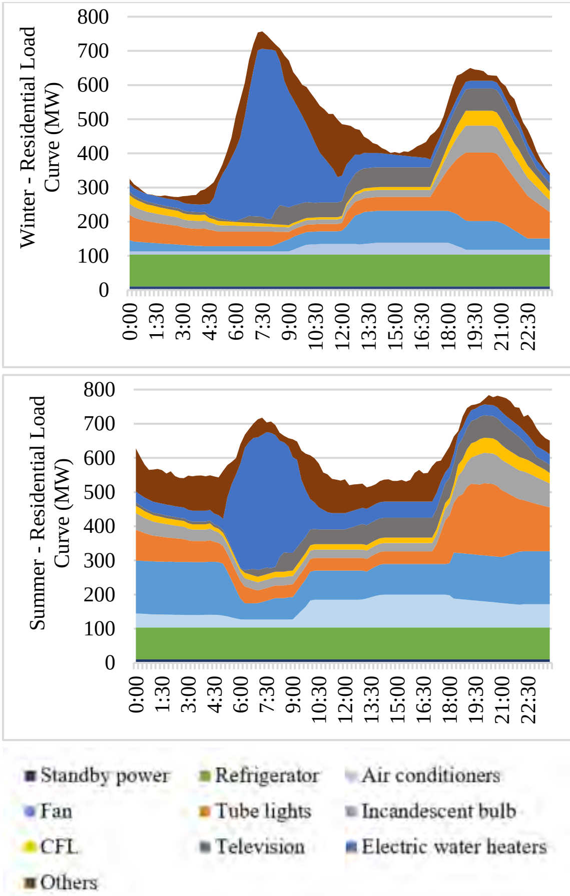

Figure 6: Average residential loads with end-use details

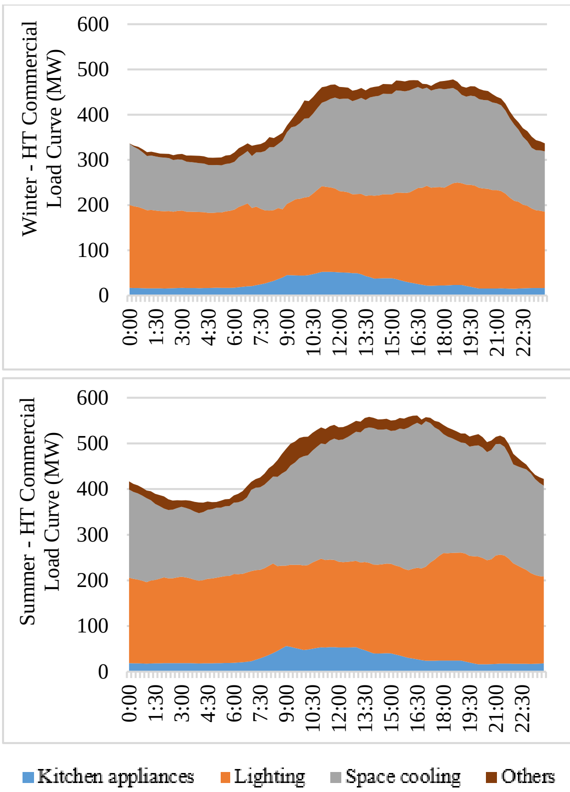

Figure 7: Average HT commercial loads with end-use details

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LT Commercial sector

BESCOM's LT commercial demand starts peaking around 13:00 and stays relatively constant until around 18:00, with some variations, in summer and winter (**Figure 8**). Average peak demand is estimated as 493 MW in winter and 644 MW in summer. Primary contributors to the peak include lighting (36% in winter, 29% in summer) and space cooling (fans plus air conditioners: 36% in winter, 50% in summer).

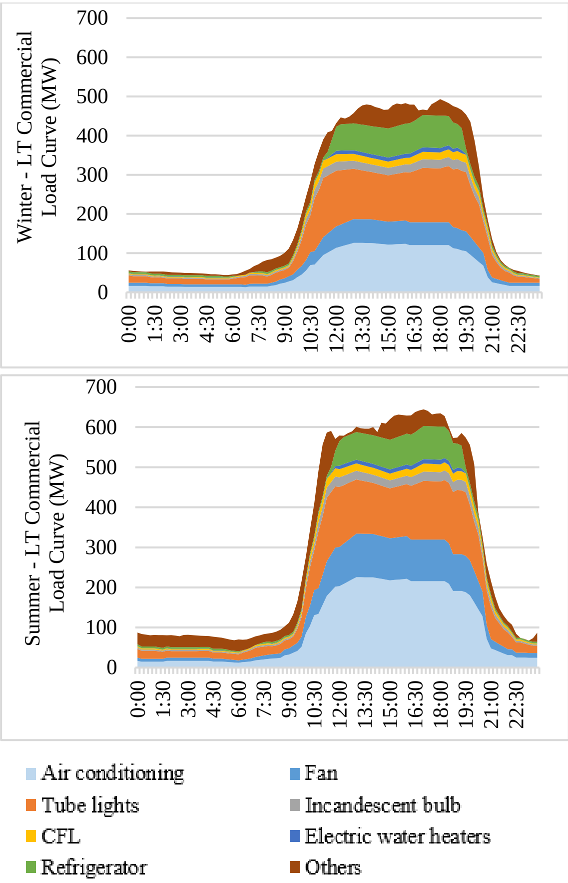

Figure 8: Average LT commercial loads with end-use details

Industrial sector

HT and LT industrial loads are based on the electrical equipment shares listed in Data and Methods section. We apply these shares equally across the day and seasons (**Figure 9**). In addition, as mentioned, industrial customers surveyed by PWC (2015) to calculate those shares include five information technology operations and two hotels that were on the industry-dedicated feeder. Thus, in reality, air conditioning share on hourly load curve could be much smaller.

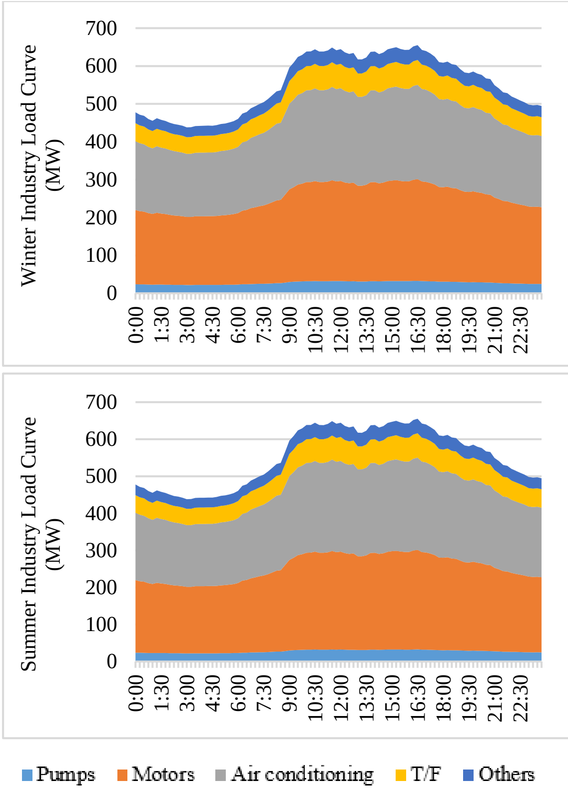

Figure 9: Average industrial loads with end-use details

Agricultural sector

Figure 10 shows the agricultural load curves in winter and summer. Based on temperature and precipitation, the patterns change significantly between seasons and even among months within a season. However, the power cut off to this sector from 6:00 to 22:00 creates large variations between maximum and average demand, particularly in the summer months: 727 MW compared to 445 MW in winter and 1,199 MW compared to 625 MW in summer.

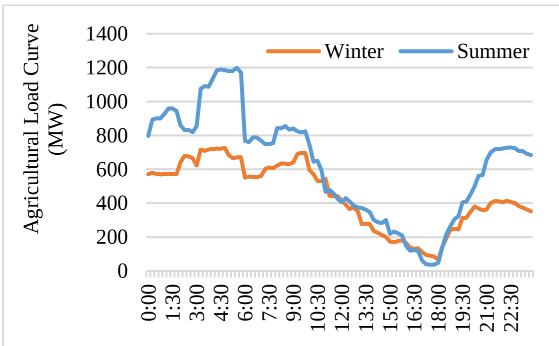

Figure 10: Average agricultural loads

END-USE DR POTENTIAL

Figures 11 shows average hourly winter and summer load curves decomposed into 34 end-uses – covering all major consuming sectors and clearly illustrating the key peak drivers. For example, the agricultural sector

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(23%) and residential electric water heaters (18%) are the primary contributors to the winter morning peak, at around 08:00; total cooling demand from all sectors (14%) are other sizable contributors. In summer, the agricultural sector's share of the peak increases to 27%, while the share from residential electric water heaters drops to 6%; the peak time of 09:30 explains the lower share of water heater demand. Total cooling demand rises to a 23% share.

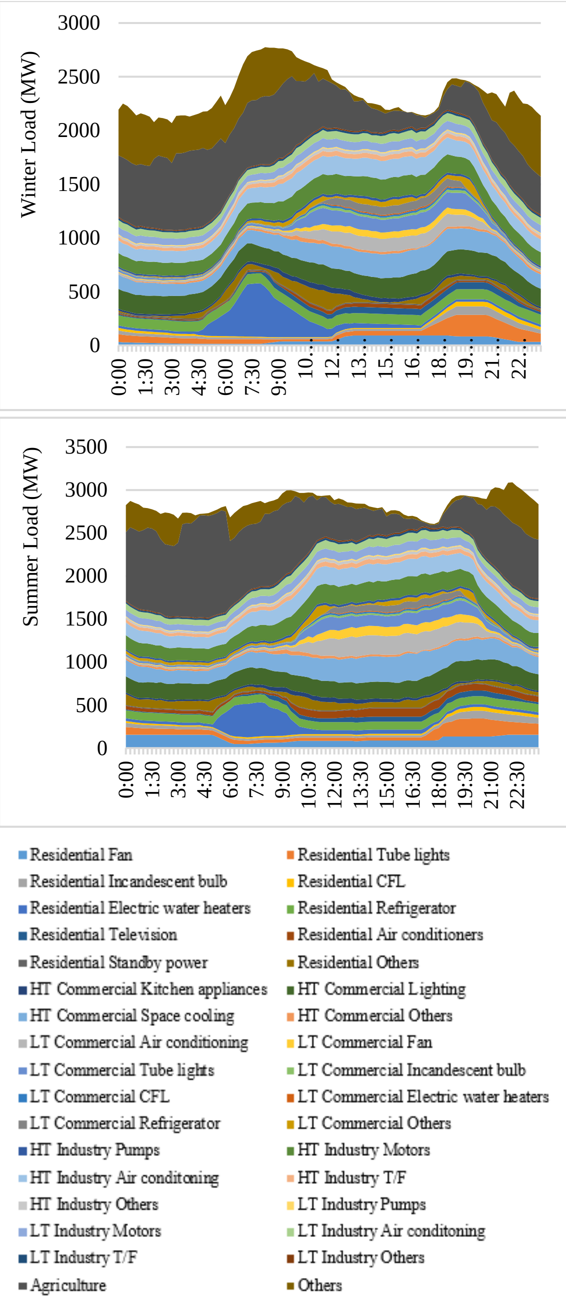

Figure 11: End-use shares on average winter and summer loads

Table 3 displays the total technical DR potentials of the key end-uses. Based on the work of Alstone et al. (2016), we have considered the following three DR services: (a) "Shift" represents DR that enables the movement of energy consumption from times of high demand to times of surplus of renewable generation or low energy market prices; (b) "Shed" describes loads that can be curtailed to provide peak capacity and support the system in emergency or contingency events—at the statewide level, in local areas of high load, and on the distribution system—with some advance notice; and (c) "Shimmy" involves using loads to dynamically adjust demand on the system to alleviate short-run ramps and grid disturbances at timescales ranging from seconds up to an hour, such as through ancillary services or frequency regulation.

Contributions from each end-use in **Table 3** are based on our stakeholder interactions in India and existing DR programs in other countries including the U.S. For example, air conditioners could offer shed service such as voluntary demand reduction or shimmy service by changing the output/set-point for a short duration such as Direct Load Control DR programs in California. Agricultural pumping cannot offer shimmy service but they can offer shift service, as already practiced by several utilities in India. Industrial consumption cannot be shifted to other hours of the day and therefore can only offer the shed service. For each end-use, **Table 3** also shows the technical DR potential in the BESCOM territory, which is the total load for that end-use.

Overall, we find that agricultural (via load shifting) and space cooling (via shimmy service) end-uses each offer ~1,000 MW of DR potential. Residential electric water heaters can also offer ~500 MW in shimmy service. The results show that shifting and shimmy services offer 1,199 MW and 1,511 MW total DR potential, respectively.

Note that **Table 3** only shows the total DR potential; further analysis is required for assessing the economic and market potentials for these services and end-uses.

Table 3: Maximum end-use DR potential in each sector

SECTOR	END-USE	MAX DR POTENTIAL (MW)	DR SERVICE
Residential	Air conditioners	96	Shed, shimmy
	Refrigerators	93	Shed
	Water heaters	497	Shed, shimmy
HT Commercial	Kitchen appliances	56	Shed, shimmy

	Space cooling	319	Shed, shimmy
LT Commercial	Air conditioners	226	Shed, shimmy
	Refrigerators	83	Shed
	Electric water heaters	11	Shed, shimmy
HT Industry	Pumps	27	Shed
	Motors	224	Shed
	Air conditioners	207	Shed, shimmy
LT Industry	Pumps	13	Shed
	Motors	107	Shed
	Air conditioners	99	Shed, shimmy
Agriculture	Agricultural pumps	1,199	Shift

CONCLUSION

This study analyzes the sectoral and end-use details of BESCOM load curves in 2016 as a way to estimate the potential for DR to reduce peak loads. The largest drivers of the winter peak, around 08:00, are the agricultural sector (23%) and residential electric water heaters (18%). The summer peak is around 09:30, and the agricultural sector's share increases to 27%, while the share from residential electric water heaters drops to 6%, mostly because hot water demand declines later in the morning while cooling demand increases across all sectors. Cooling demand from all sectors contributes 23% to the peak in summer, compared with 14% in winter. Overall, we find that agricultural and space cooling end uses each offer ~1,000 MW of DR potential – agricultural pumps offering load shifting service while space cooling offering shimmy service. Residential electric water heaters can also offer ~500 MW in shimmy service. The results show that shifting and shimmy services offer 1,199 MW and 1,511 MW total DR potential, respectively.

Our results entail several caveats and limitations. Assumptions around variables—penetration of end-uses in particular—are subject to uncertainty. All of our end-use inputs are based on survey data, but the survey samples might not accurately represent the entire population. To address this concern, we held multiple workshops to address data issues with the BESCOM team, and the final results and trends were validated by BESCOM experts. As an example, if we changed the penetration of residential electric water heaters to 15% and 25%, the DR potential of this end-use would be ~390 and 650 MW. In addition, because Karnataka (including the BESCOM territory) experienced power cuts in 2016, feeder-level actual load data may exclude significant pent-up demand, especially from the residential and LT commercial sectors. As a result, total load and DR potential estimated in this study may be underestimated.

Our future work may include refining our analysis by using end-use level temporal consumption data, assessing the cost-effectiveness of different DR services, assessing the strategies for dispatching the DR for load management by the utility, and leveraging this analysis to assess the future peak load impacts of certain key end-uses such as air conditioners.

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REVIEW OF THE EXISTING TARIFF FRAMEWORK FOR ELECTRIC VEHICLE CHARGING IN INDIA

Bhawna Tyagi[1], Chandana Sasidharan[2], Shyamasis Das[3]

[1]*Power Utilities and Electric Mobility Alliance for an Energy Efficient Economy,* Delhi, India
bhawna@aeee.in

[2]*Power Utilities and Electric Mobility Alliance for an Energy Efficient Economy,* Delhi, India
chandana@aeee.in

[3]*Power Utilities and Electric Mobility Alliance for an Energy Efficient Economy,* Delhi, India
shyamasis@aeee.in

ABSTRACT

Deployment of a robust charging infrastructure is essential for the sustainability of the Electric Vehicle (EV) ecosystem. The installation of charging stations is increasing with the penetration of EVs for public use in the major cities. However, the commercial viability of the public charging stations is linked with the development of an appropriate tariff framework for EVs. Also, the tariff framework is designed such that DISCOMs are able to operate efficiently by incorporating the additional demand from EV charging. EVs represent an addition to the existing load in the distribution system from the public charging stations and the charging at residences and offices.

Most of the regulators of States and Union Territories have already announced EV specific tariff rates in their respective tariff orders. A review of the existing EV tariff framework in India is important as the EV penetration is increasing. The paper presents a study of the current EV specific tariffs in India. The key questions that paper focuses on are variation in state-specific EV tariff rates, categorization of EV tariff, demand and energy charges and the introduction of Time of Day /Time of Use specific EV tariff rates. The paper observes that all states have quite unique tariff structures for EV charging. However, EV charging as a consumer category is distinct from other types of consumers due to three salient aspects: mobile source of electric requirement, uneven load and bi-directional energy flow. As a result, regulators have to consider these factors while framing the tariff schedule.

Keywords—Electric Vehicle (EV), Tariff, State DISCOMs, Energy Charge, Demand Charge

INTRODUCTION

Road transport continues to be an oil guzzler in India. Presently, it accounts for about 59% of total energy consumption (~ 52,296.54 ktoe) in the transport sector (MOSPI, 2019). Due to its continued dependence on oil, it has significant implications on the environment through its contribution to GHG emissions and criteria pollutants such as NOx, SOx, CO, HC, $PM_{2.5}$, etc.

As the Indian economy is rapidly growing, transport demand is expected to increase further over the next several decades. According to a report by Niti Aayog (2018), the demand for oil in the transport sector is expected to register more than a two-fold jump by 2032. To reduce its oil dependence and resolve the issue of pollution, the electric vehicle (EV) has been identified as a potential opportunity by the Government of India to achieve this target. In 2012, India released its National Electric Mobility Mission Plan (NEMMP) 2020, which aimed to promote hybrid and electric vehicles to enhance national energy security, mitigate adverse environmental impacts (including CO2) from road transport vehicles and boost domestic manufacturing capabilities for electric vehicles (Government of India, 2012). Followed by this, the Government of India launched Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles (FAME) in April 2015. FAME is an incentive scheme which aims to reduce the upfront purchase price of hybrid and electric vehicles to stimulate early adoption and market creation of hybrid and electric vehicles (Government of India, 2015).

Intially, government proposed to shift all public transport and 30% of private vehicles to electric by 2030. However, in April 2017, Government of India announced its vision to electrify its entire vehicle fleet by 2030 to promote zero-emission technologies (UPERC, 2019). Recently, second phase of the Faster

Adoption and Manufacturing of Electric Vehicles (FAME) scheme has been launched. The scheme is proppposed to be implemented over a period of 3 years for faster adoption of electric mobility and development of its manufacturing ecosystem in India (Government of India, 2019). Vehicles eligible under FAME II scheme will cumulatively save 5.4 Mtoe of oil demand resulting in a net reduction of 170 PJ of energy and 7.4 Mtons of CO_2 emissions over a lifetime. The electric buses subsidized under FAME II will account for nearly 3.8 billion vehicle kilometers traveled over their lifetime (IEA, 2018).

To facilitate electric vehicle adoption, infrastructure development is one of the major requirements other than government policies and incentives. This comprises of two components mainly, availability of public charging stations and capacity to cater to the increase in electricity demand from EV charging. While additional electricity sales due to EV charging would help increase the revenue volume of a distribution utility, charging demand may accentuate the peak load of the service area and have a significant bearing on the cost of power procurement for the distribution utility. This apart, it may incur additional cost for network upgradation. As a result, tariffs for EV charging will be a critical factor for the utility to cater to the charging demand.

Therefore, it becomes pertinent to the review of the existing EV tariff framework in India. The paper presents a study of the current EV specific tariffs adopted by different states and union territories. The key questions that will be focused are variation in state-specific EV tariff rates, categorization of EV tariff, demand and energy charges and the introduction of Time of Day (TOD)/Time of Use (TOU) specific EV tariff rates. The study also identifies key considerations for developing the EV tariff framework which will assist regulators in developing an appropriate tariff framework.

STATE SPECIFIC EV TARIFFS

Following the clarification issued on 13th April 2018 by the Ministry of Power (MoP) regarding delicensing of the EV charging activity, a handful of states such as Delhi, Karnataka, Haryana, and Maharashtra announced EV specific tariff rates. However, at that time, there was no specific direction or guideline with respect to tariff determination for EV charging. On 14th December 2018, MoP issued "Charging Infrastructure for Electric Vehicles – Guidelines and Standards -reg." to promote affordable EV adoption in the country. Among a range of measures, the guideline sheds clarity on the possible electricity tariff for EV charging. It provides the guidance that the tariff to be determined by the appropriate commission should not exceed the average cost of supply (ACoS) by more than 15%. The guideline also allows setting up of captive or domestic charging stations which will attract tariffs applicable for those consumer-categories. Several states such as Uttar Pradesh, Telangana, Andhra Pradesh, etc. have announced EV specific tariffs keeping the MoP guideline as a basis.

Table 1 gives a snapshot of the state-wise tariffs (energy charges and demand charges) for EV charging at public charging stations. It also provides comparison of EV tariffs with residential and commercial tariffs. For most of the states, EV tariff rates varies from ₹ 4/kWh to ₹ 6/kWh. Uttar Pradesh is the only state with tariff rate of more than ₹ 7/kWh for EV Charging stations. In comparison with other categories, EV specific tariff rates are higher than their residential tariff and lower than their commercial tariff rates. This hold true in most of the States and UTs.

HIGHLIGHTS OF STATE SPECIFIC EV TARIFF FRAMEWORKS

Most of the regulators of States and UTs have already announced EV specific rates in their respective tariff orders (**Figure 1**). However, the consideration related to EV specific tariff is not the same across states. Some states introduced a separate category called Public EV Charging stations (such as UTs, Goa, Punjab, etc.) which is distinct from existing consumer categories. However, some states have specified tariffs for EV under the existing categories such as non-domestic or non-commercial category (such as Andhra Pradesh, Chhattisgarh, and Punjab). Jharkhand is the only state which introduced EV tariff under the commercial category. Such categorization of EV specific tariff rate will have an implication on the commercial viability of EV charging business as tariff rates under commercial category is significantly higher than residential or domestic category as shown in **Table 1**.

Most of the EV charging tariff is a flat/ energy rate. However, some states have taken additional steps and specified tariff separately for LT and HT customers (such as Delhi, Uttar Pradesh, Andhra Pradesh, Maharashtra, Gujarat, etc.).

Table 1: Comparison of EV specific tariff rates with Residential and Commercial tariff rates announced by selected States

ISSUING AGENCY	STATE	RESIDENTIAL TARIFF		COMMERCIAL TARIFF*		EV TARIFF		YEAR
		ENERGY CHARGE	DEMAND CHARGE	ENERGY CHARGE	DEMAND CHARGE	ENERGY CHARGE	DEMAND CHARGE	
DERC	Delhi	₹ 3 to ₹ 7.75/kWh	₹ 125 to ₹ 250/kW per month	₹ 8.0/kVAh	₹ 250/kVA per month	₹ 5.5/kWh and ₹ 5.0/kVAh	Nil	FY19
UPERC	Uttar Pradesh	₹ 3 to ₹ 6.5/kWh	₹ 50 to ₹ 100/kW per month	₹ 5 to ₹ 18/kWh	₹ 95 to ₹ 430/kW per month	₹ 5.9 to ₹ 7.7/kWh	Nil	FY19
GERC	Gujarat	₹ 1.5 to ₹ 5.2/kWh	₹ 15 to ₹ 70 per month	₹ 4.35 to ₹ 4.65/kWh	₹ 50 to ₹ 195/kW per month	₹ 4 to ₹ 4.1/kWh	• ₹ 25 per month per installation • ₹ 25 to ₹50 per kVA per month	FY20
KERC	Karnataka	₹ 7.02 to ₹7.80/kWh	₹ 45 to ₹ 70/kW per month	₹ 6.40 to ₹ 9.0/kWh	₹ 65 to ₹ 95/kW per month	₹ 5.00/kWh	₹ 60/kW per month and ₹ 190/kVA per month	FY20
MERC	Maharashtra	₹ 4.6/kWh	₹ 190/kVA per month	₹ 3.9 to ₹ 4.35/kVAh	₹ 190 to ₹ 220/kVA per month	₹ 5.06/kWh	₹ 70/kVA/ Month	FY20
APERC	Andhra Pradesh	₹ 1.45 to ₹ 9.05/kWh	Nil	₹ 5.4 to ₹ 10.15/kVAh	₹ 55 to ₹ 75/kW per month	₹ 5/kWh and ₹ 5/kVAh	Nil	FY20
TSERC	Telangana	₹ 1.45 to ₹ 9.5/kWh	Nil	₹ 5.3 to ₹ 12.0/kVAh	₹ 50 to ₹ 60/kW per month	₹ 6.00/kWh	Nil	FY19
CSERC	Chhattisgarh	₹ 1.0 to ₹ 2.45/kWh	₹ 2.40 to ₹ 4.85/kWh	₹ 5.40 to ₹ 7.25/kWh	₹ 50 to ₹ 180/kW per month	₹ 5/kWh	Nil	FY20
MPERC	Madhya Pradesh	₹ 3.1 to ₹ 6.3/kWh	₹ 35 to ₹ 90 per connection	₹ 6.1 to ₹ 8.5/kWh	₹ 55 to ₹ 260/kW per month	₹ 5.9 to ₹ 6.0/kWh	₹ 100 per kVA to ₹ 120 per kVA of Billing Demand	FY19
PSERC	Punjab	₹ 4.99 to ₹ 7.41/kWh	₹ 35/kW to ₹ 80/kVA per month	₹ 6.32 to ₹ 7.29/kWh	₹ 45/kW to ₹ 110/kVA per month	₹ 6/kVAh	Nil	FY20
BERC	Bihar	₹ 6.15 to ₹8.60/kWh	₹ 20 to ₹ 40/kW per month	₹ 6.4 to ₹ 7.5/kWh	₹ 30 to ₹ 180/kW per month	Same tariff for EV as the respective category rate	Nil	FY20
OERC	Orissa	₹ 2.5 to ₹ 5.7/kWh	Nil	₹ 5.4 to ₹ 7.1/kWh	₹ 200 to ₹ 250/kVA per month	₹ 4.2 to 5.7/kWh	Nil	FY20
HERC	Haryana	₹ 2.7 to ₹ 7.1/kWh	Nil	₹ 6.35 to ₹ 7.05/kVAh	₹ 160/kW per month	₹ 6.5/kVAh	₹ 160/kW or 160/kVA	FY19

Source: Tariff Orders of respective States for Year 2018-19 and 2019-20

**Commercial considered as non-domestic by various SERCs.*

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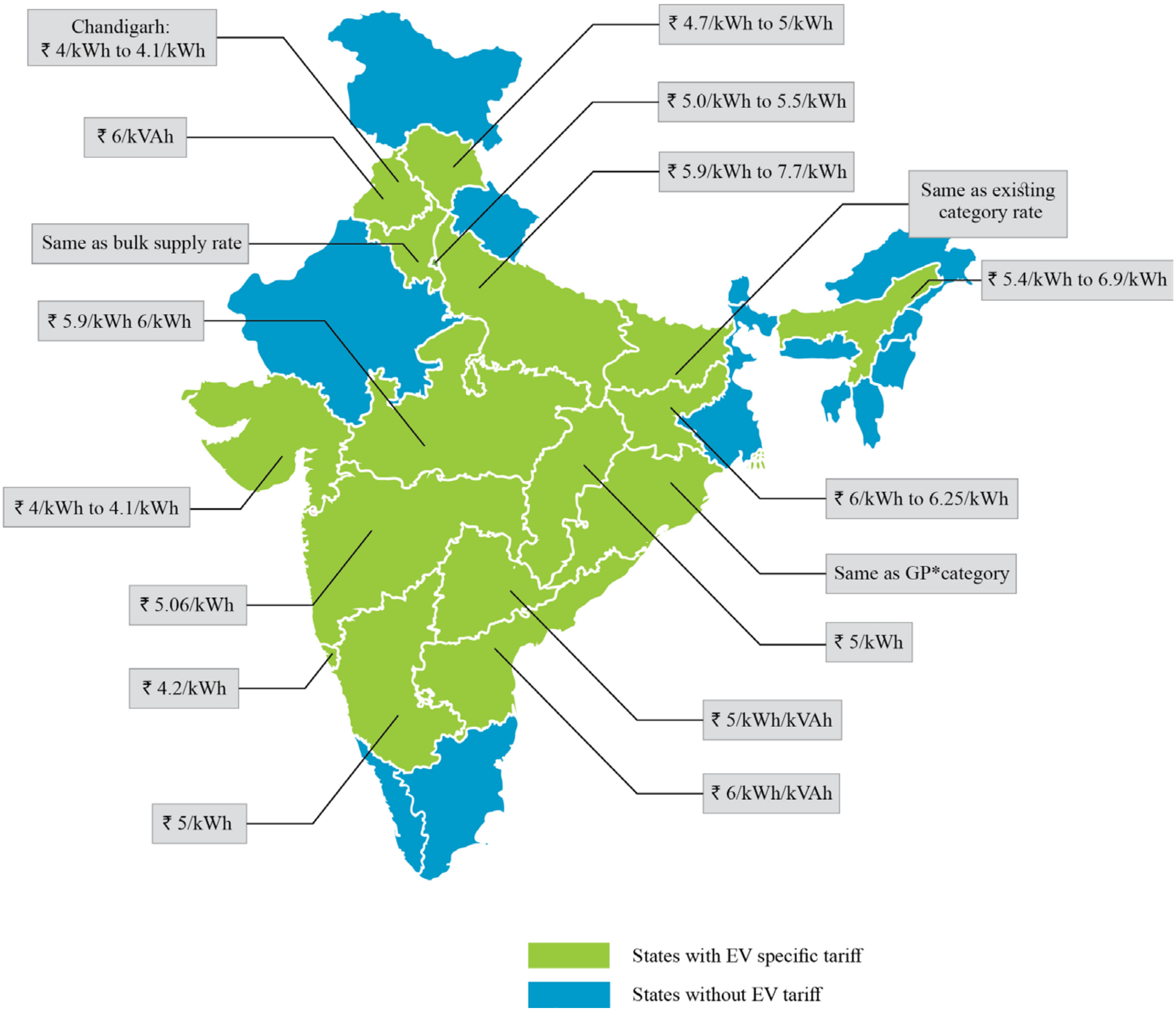
Figure 1: Map showing States with and without EV specific Tariff rates



Source: Own Construction based on tariff orders of States of FY19 and FY20
**GP: General Purpose Category*

The tariff for the sale of electricity generally comprises of two parts -- Fixed/ Demand charge and Variable/ Energy charge. Few states have introduced demand charges which include Maharashtra (₹ 70/kVA/month), Karnataka (for LT connection ₹ 60/kW/month and for HT connection ₹ 190/kVA/month), Haryana (₹ 160/kW or 160/kVA), Gujarat (for LT ₹ 25 per installation and for HT connection from ₹ 25-50/kVA/month), Madhya Pradesh (for LV ₹ 100/kVA/month and for HV ₹ 120/kVA/month), among others. Joint Electricity Regulatory Commission (JERC) has announced the same demand charge of ₹ 100/kWh for Goa and UTs including Chandigarh, Andaman & Nicobar Islands, Lakshadweep and Daman & Diu. Regulatory commissions in some states such as Delhi, Andhra Pradesh, Uttar Pradesh, Bihar, Punjab, Chhattisgarh and Telangana have also introduced single part tariff with no demand charge to incentivize EV adoption.

On the other hand, the state regulatory commissions have introduced flat rates for energy charges and these are found to vary depending on types of electricity connection. Presently, LT energy charge varies from ₹ 4.1/kWh in Gujarat to ₹ 7.7/kWh in Uttar Pradesh. HT energy charges vary from ₹ 4/kVAh in Gujarat to ₹ 7.3/kVAh in Uttar Pradesh. Bihar Electricity Regulatory Commission (BERC) is the only exception which specified same energy charge for both LT and

HT connections for EV charging. Jharkhand announced a separate tariff for rural and urban consumers under the commercial category – ₹ 6/kWh and ₹ 6.25/kWh respectively, which are applicable to EV charging. In the case of Andhra Pradesh, APERC made a significant change in its EV tariff structure from FY19 to FY20. Initially, APERC introduced two different tariff rates for HT and LT -- ₹ 5.95/kWh and ₹ 6.95/kWh respectively for FY19. They also specified ToD rates for FY19. However, in FY20, APERC has introduced a single part flat tariff for both HT and LT and removed ToD charges to encourage EV adoption. In addition to energy and demand charges, other surcharges are also applicable for EV charging in most of the states such as Late Payment Surcharge (LPSC), Power Purchase Adjustment Cost (PPAC), etc. Maharashtra also specified wheeling charges of ₹ 0.94/kWh for both LT and HT EV charging stations.

ToD or ToU rates have been successfully used by other countries to incentivize consumers to shift their charging time to off-peak hours. It becomes crucial to examine such rates in the case of India. There are only a few regulatory commissions (DERC, UPERC, and MERC) that have introduced ToD rates specifically for EV charging. In the case of Delhi, ToD rates are only applicable for consumers with a load above 10kW/kVA. DERC has specified ToD surcharge and rebate for peak and off-peak hours at 20%. In Uttar Pradesh, the same surcharge and rebate rate is at 15%. In contrast to Delhi and Uttar Pradesh, Maharashtra has stipulated absolute amounts of surcharge and rebate instead of a percentage. They levied an additional charge of ₹ 0.80 / kWh for usage from 09.00 hours to 10 hours and ₹ 1.1/kWh from 18.00 hours to 22.00 hours. They offered a rebate of ₹ 1.50/kWh for usage between 22.00 hours to 06.00 hours.

Overall, the introduction of MoP guideline has given a direction in terms of fixing tariffs for public EV charging stations. However, the consideration related to EV specific tariff is not the same across states. Based on the study of existing tariff frameworks, the key takeaways relevant for developing the EV tariff framework are discussed in the next section.

KEY TAKEAWAYS

From the review of the EV charging tariff schedules across the states and UTs and the current studies, this investigation identifies nine areas that warrant specific deliberations.

First, the categorization of EV charging in the tariff order. Presently, different DISCOMs have adopted different approaches for EV charging. It is currently categorized as non-residential, commercial, non-industrial or bulk supply. In some cases, a separate category is also created for public charging stations. Such categorization of EV specific tariff rate will have an implication on the commercial viability of EV charging business as tariff rates under commercial category is significantly higher than residential or domestic category. Also, there is a need to provide EV customers with clear electricity price signals.

Second, the applicability of demand charge on electricity supply to EV consumers. Some states have not levied demand charge stating reasons such as to encourage EV adoption. There is no clear directive whether the demand charge should be socialized to all consumers or restricted to the EV category.

Third, the use of TOD/TOU rates to encourage charging during off-peak hours to facilitate DISCOMs in peak demand management. EVs represent a significant addition to demand at a micro level compared to the macro level. The average sanctioned load for domestic consumers in India is approximately around 3 kW and the average size of an EV charger for home charging is 2.5 kW. Therefore, in terms of energy consumption and power demand, an additional charging station is similar to an additional household on the grid (Coingard et al., 2019). Few states have already announced the TOD rates for EV consumers such as Delhi, Uttar Pradesh, etc. However, a large number of states haven't considered this in planning to accommodate EV load.

Fourth, the definition of public charging stations (PCS) remains vague. Private charging is defined as charging done at residence and anything done outside the home premises considered as public chargers (MoHI &PE order, 2017). No clear definition has been provided in the MoP order (2018).

Fifth, the applicability of open access charges for EV public charging stations. Maharashtra is the only state which has specified the wheeling charges for EVs.

Sixth, the applicability of PPAC and other surcharges in case of EV tariff. This will have a significant impact on tariff rates for EV consumers.

Seventh, the tariff for bus charging, whether bus depot charging will be considered as PCS or existing tariff for STUs will be applicable.

Eighth, there is no information on the maximum size of Electric Vehicle Supply Equipment (EVSE) which homeowners can install and whether they need a separate connection for EVSE or not. Also, in the case of a multi-story building which tariff rate will be applicable. Except for Uttar Pradesh, none of the states has clarified on these aspects in the tariff order.

Ninth, there is no information on whether the entire investment should be socialized to all the consumers of licensee or investment should be charged only to EV users. The tariff impact assessment in these two scenarios is crucial to ensure that it doesn't hamper the case for EVs.

DISCUSSION AND CONCLUSION

The tariff landscape in India is very complex and diverse. As reflected in the previous sections, almost all states have quite unique tariff structures for EV charging. It is also observed that in just one year of introducing separate tariffs for EV charging, some states brought changes in the EV tariff structures. This could be attributed to the evolving understanding of this new consumer category. DISCOMs and regulators are trying to figure out the characteristics of this new demand, which is not a straightforward exercise. EV charging as a consumer category is distinct from other types of consumers because of the following three salient aspects:

- **Mobile source of electricity requirement** – Unlike the other consumer-types such as residential, commercial, industrial or public utility, EVs are mobile and although their charging points are stationary, the electricity and power demand at the charging places could be very dynamic and at least in initial days, very unpredictable till there is sizeable number of EVs on road.
- **Uneven load** – Utilities, load despatch centers and regulators are more accustomed to managing smooth load curves with peaks and valleys. Electricity grid stability is vulnerable to uneven load curves, which may cause power cuts at local (division), zonal, state and sometimes, at regional or national levels (the latter is termed as blackout). As EV charging loads at charging points are anticipated to be very dynamic with spikes in the demand curve, there is serious concern regarding the impact on the distribution network, especially in distribution areas with low available hosting capacities. Fast charging of heavy-duty EVs with large batteries is envisaged to have the maximum impact on the load curve and the distribution network.
- **Bi-directional energy flow** – EVs are more than a consumer; they are a potential supply-side resource too. Batteries being the core of EVs, the latter can be effectively leveraged as a Distributed Energy Resource (DER) using Vehicle-to-Grid (V2G) functionality. An analogy can be drawn with a prosumer such as a building having a rooftop solar plant with a net metering facility, where the connection can draw from as well as feed electricity to the grid. Hence, appropriate metering and tariff-setting would be required to enable the application of EVs as a Virtual Power Plant (VPP).

Presently, most of the tariffs are promotional in nature. The regulators have to take the above-mentioned factors into account while framing the tariff schedule. There is a need to bring clarity to provide EV customers with clear electricity price signals which have implications on the commercial viability of EV charging business. In the current scenario, ToD could be considered to shift EV load in off-peak hours. But over time when there will be a sizeable number of EVs on road, ToU tariff rates could be considered as EV charging is dynamic in nature i..e EV charging can happen anywhere.

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EFFECTIVENESS AND BALANCE: A CANADIAN REGULATOR'S APPROACH TO REVIEW OF ENERGY EFFICIENCY FUNDING PROPOSALS

Jackie Ashley

British Columbia Utilities Commission.
Vancouver, B.C., Canada
Jackie.ashley@bcuc.com

ABSTRACT

In a constantly changing market, and with many new ideas for energy efficiency programs, how do you determine which suite of programs are in the public interest? In British Columbia, one approach is attempting to demystify the various cost-effectiveness tests by looking at the question from the perspective of 'effectiveness and balance':

- **Effectiveness** - how effective is the energy efficiency program in 'nudging' a customer to change their behaviour or investment decision? This is a two-step process: First, ensure the program addresses a societal problem by ensuring the value of energy saved (plus any non-energy benefits) exceeds the cost to the customer of the investment. The second step is to see if the utility's program is cost-effective in addressing the problem.
- **Balance** - do all customers have a reasonable opportunity to benefit from energy efficiency programs? This requires reviewing whether energy efficiency programs provide broad opportunities for customers to participate, in particular for 'hard to reach' customers such as low-income groups, rural communities, and renters.

This paper will discuss in greater detail the 'effectiveness and balance' approach to reviewing energy efficiency programs.

Keywords—energy efficiency, demand-side management, cost-effectiveness tests, regulator, British Columbia

INTRODUCTION

Energy efficiency programs encourage customers to be more efficient in their use of energy. However, they also require a source of funding, and it can be difficult to explain why utilities should fund programs that encourage customers to use less (rather than more) of their product. In addition, customers may complain that these programs are unfair as they typically increase rates and not all customers (in particular low-income customers) benefit from them.

To obtain funding for energy efficiency programs it is therefore critical to be able to explain in 'plain English' why it is in the public interest for these programs to be funded, and to address equity concerns around who pays and who benefits.

This paper puts forward an 'Effectiveness and Balance' response to this issue based on the approach used in British Columbia (BC), Canada which may assist organizations secure funding for their own cost-effective and balanced energy efficiency programs.

The model described here has its origins in the cost-effectiveness tests described in the 2001 California Public Utilities Commission Standard Practice Manual. In 2008, the BC government enacted the Demand-Side Measures Regulation (Regulation) which outlined the cost-effectiveness tests to use in British Columbia and programs that must be included to ensure a balanced portfolio (such as low-income and educational programs).

In 2014, the British Columbia government updated the Regulation to recognize emissions reduction and non-energy benefits and allow utilities to claim a portion of savings from any code or standard towards which market transformation activities were targeted. In the same year, the British Columbia Utilities Commission published a decision which applied the Regulation to a utility's funding request, and it is this decision which forms the foundation for the model described in this paper. Additional refinements have been made since that date, including minimum levels of funding required for programs that provide direct support to governments crafting new codes and standards promoting efficiency, and the appropriate test to use for utility electrification programs that increase load.

Undoubtably this model will continue to be refined in the future.

CORE ASSUMPTIONS

Before getting into the details of developing and evaluating energy efficiency programs, it is important to start with a definition of 'success' that is shared by all parties involved.

Defining 'Success'

Should 'success' be defined as only focusing on efficient *supply* of electricity, or do we also care about whether the customer is efficient in their *use* of electricity once it is delivered?

In British Columbia, 'success' is defined as customers receiving the heat, light, power, (and now with the advent of electric cars, even transportation) at the lowest total cost. This means that we focus on the whole market - promoting both the efficient supply and efficient use of electricity.

Customers in jurisdictions with this 'whole market' definition of success will therefore receive the services they need (heat, light etc.) at a lower overall cost than jurisdictions who only focus on the supply side of the market.

This broader definition of 'success' (promoting both the efficient supply and efficient use of electricity) is the one adopted in this paper.

Aligning Incentives

Steps to improve the efficiency of the demand side of the market require a source of funding and an entity to deliver the programs. It is important that all parties involved share the same definition of success.

As mentioned previously, companies operating in a competitive environment are generally not in the business of helping their customers use less of their product. This is because the lower sales would typically result in lower profits.

However, regulated companies are different. In their case the regulator determines how much profit the utility is allowed to earn, adds on allowed costs, and then uses an estimate of future sales volumes to set the rates to be charged. The regulator can therefore assure the utility that it will be able to recover the cost of energy efficiency programs in its rates, and can even provide the utility with a financial incentive to run these programs effectively.

For example, where it is cheaper for the utility to meet customers need for energy through energy efficiency programs rather than new supply options, the regulator can require and incent a regulated utility to take on this additional role.

Where it is not possible to fully mitigate a utility's incentive to sell more (rather than less) of its product, or where there is a desire to offer programs that targets more than one fuel source (such as electricity and heating oil) an alternative option is for the utility to provide the funding for energy efficiency programs (and recover those costs in its rates), but for an independent third party to design and deliver the energy efficiency programs. This approach is used in Nova Scotia.

EFFECTIVENESS

Once we have established a definition of 'success' as promoting both the efficient supply *and* use of electricity, we need to identify where customers are wasting electricity and design cost-effective programs to reduce waste. The following two step approach has been developed:

Step One: Is There a Problem?

How do we know when a customer is wasting electricity, for example by continuing to use inefficient equipment or by not using the equipment that they have in an efficient way?

The analysis that identifies where waste is occurring is referred to in British Columbia as a 'Conservation Potential Review'. This starts with a list of alternative investment decisions available to the customer that could improve efficiency (such as investing in efficient motors, lightbulbs, insulation etc.) or customer behaviours (such as turning off lights when not in use).

The Conservation Potential Review then estimates if the cost to the customer of becoming more energy efficient is lower than the cost to the utility of the energy that is being wasted. If the answer is yes, it is then in the public interest to 'nudge' the customer into making that investment decision/behaviour change.

For example, let's say we wanted to find out whether it is in the public interest to 'nudge' a customer into replacing their incandescent lightbulbs with LED bulbs. To do this, we would compare the cost of the LED lightbulb with the value of electricity saved over the expected life of the LED lightbulb. If the value of electricity saved exceeds the cost of the LED lightbulb, it would pass this test.

There are some nuances in this calculation:

- **Cost of the investment:** this represents the incremental cost to the customer of making the energy efficiency investment (including the cost of their own time) before any incentives are received from energy efficiency programs. If this test is done on the proposed energy efficiency program, it will also include the costs of administering the program.
- **Value of energy saved**: the value of energy saved is not the reduction in the customer's bill, but the utility's avoided costs. If the energy saved is over the long term, a long-run avoided cost should be used. As the energy saved is at the customer's meter, the value should also include avoided: incremental network losses; network upgrade costs; and generation reserves. Adjustments may also be appropriate to reflect the beneficial seasonal and within-day shape of energy saved.
- **Emission reduction:** The energy saved is equivalent to 'clean' electricity, and so the value of emission reductions should also be included as a benefit in the calculation. This could be undertaken by pricing the CO_2 saved at an appropriate value, or (as used in British Columbia) valuing the energy saved at the avoided cost of clean electricity.
- **Non-energy benefits/drawbacks:** Some energy efficiency investments have other non-energy benefits (for example, double glazed windows can offer noise reduction, an insulated house can offer health and comfort benefits). As a result, 'nudging' the customer to make these types of investments can still be in the public interest even if not all the costs are recovered through energy savings. In British Columbia, these non-energy benefits may be estimated and included in the calculation.

  To the extent that there are non-energy drawbacks (for example, where the more efficient product is less aesthetically pleasing to the customer), this can also be considered.

This first test (which can be referred to as a total resource cost test or societal test depending on the inputs used) can be considered an initial screening test. It ensures that the energy efficiency program is 'nudging' the customer into making a decision that makes sense from a societal perspective. There may be some investments that do not pass this initial screening test but which may be still in the public interest – for example, a new technology where costs are expected to decrease in the future. Some level of judgement in interpreting the test result is therefore required.

In undertaking this analysis, it is important that the list of potential new investment opportunities reviewed is kept current. Otherwise there is a 'picking winners' risk where the energy efficiency programs 'nudge' customers to invest in a particular product when there is a better product available on the market.

This test can also be used to determine if it is in the public interest to 'nudge' a customer to switch from a fossil fuel for their energy needs (cooking, heating, power, transportation etc.) to cleaner electricity. In this case, the test would be to see if the total cost of electricity as defined above (energy, emissions, non-energy benefits/drawbacks) is lower than the total cost of the fossil fuel currently being used.

It is important to note that this screening test does not include the size of any incentive provided to the customer to 'nudge' them into making an energy efficient investment – it therefore only identifies if there is a problem and not whether the energy efficiency program is effective in addressing the problem.

For example, an energy efficiency program to encourage customers to invest in LED lights could include proposals to give away \$1, \$10 or even \$100 with every \$5 lightbulb purchased, and these different incentive levels would not affect the results of this first screening test. As a result, even if a program passes this step, it is important to continue to step two below.

Step Two – Can the Utility Fix the Problem?

Once you have identified the investments or behaviours customers should be making to reduce waste (Step One), the next step is to determine if it is cheaper for the utility to 'nudge' the customer to be more efficient in their use of electricity, or to continue to supply the electricity that is being wasted.

This step is typically undertaken in a utility's Integrated Resource Plan (a longer-term outlook of how the utility intends to meet forecast demand), where several energy efficiency portfolio options can be evaluated against supply side options. However, this test can also be performed on an individual energy efficiency program by program basis.

Developing and evaluating energy efficiency programs requires (i) identifying the market barriers preventing a customer from making efficient decisions regarding their energy use and designing programs to mitigate those market barriers (and so 'nudge' the customer into making efficient decisions), and (ii) estimating whether the cost of these energy efficiency programs is lower than the utility's cost of supplying the electricity that is being wasted.

(i) Design programs to mitigate market barriers.

This step requires a very good understanding of the customer to identify why they are being inefficient in their use of electricity, together with marketing expertise to determine how best to 'nudge' the customer into changing their behaviour. If the utility does not already have this expertise they will need to acquire it.

Customer end-use surveys can be a useful tool in developing energy efficiency programs for segmented markets. In BC, residential and commercial end-use surveys capture a range of building characteristics, fuel choices and installed appliances, energy-use behaviours, customer economic background and attitudes towards energy issues. This dataset can then be 'sliced and diced' to help design programs targeted at different customer segments. Market barriers preventing customers from being efficient in their energy use could include a requirement for a short payback period (for example, a customer desire for a 2-year payback period when the investment's payback period is 4 years). In this case, a program to 'nudge' a customer to make the energy efficient investment might include a utility incentive to shorten the payback period.

Market barriers could also include a lack of information or time, for example where energy efficiency is not a key priority for the customer. In this case, a program to reduce the 'hassle factor' for the customer (such as providing subsidised energy audits and/or energy efficiency managers to commercial and industrial customers) may be appropriate. Other market barriers could include a lack of available product and/or product awareness, in which case working with suppliers and trade organizations can be an effective option. For example, in BC one utility runs a Trade Ally Network program that develops and maintains a contractor network to promote energy efficiency programs and customer messaging.

Low cost ways to encourage increased energy efficiency can also include the utility providing resources to various levels of governments to assist in the development of new codes and standards (such as improved building codes), or the development of rate designs (such as inclining block rates) which can reduce payback periods for customers. In British Columbia, utilities are required to devote a minimum level of their energy efficiency portfolio spending to support the development and enforcement of energy efficiency related codes and standards.

Partnerships with other trusted service providers (such as low-income and affordable housing associations, community groups) can also be an effective way of delivering energy efficiency programs to target market segments.

In addition, while it can be useful to review energy efficiency program offerings of other jurisdictions, programs that work well in one jurisdiction may not always work well in others. There may also be a benefit from developing targeted programs for different customer sub-groups, for example programs offered in rural areas may be more effective if designed differently from those offered in cities.

(ii) Evaluate cost-effectiveness of programs.

Once energy efficiency programs are designed, the last part of the effectiveness step is to estimate whether it is cheaper for the utility to 'nudge' the customer into making these energy efficiency investments (or behavioural changes) or supply the energy that would otherwise be wasted. It can be useful to show this test result as a $/MWh or ¢/kWh of energy saved from the energy efficiency program.

Unlike Step One, where we determine if there is a 'problem', the test in Step Two (also called the utility cost test) includes the cost of any incentive provided by the utility. If an energy efficiency program does not pass this test, it could be an indicator that the program is not effective in targeting the market barrier (for example, the market barrier could be around lack of time/information while the program is focused on offering incentives). It could also be that a significant level of the benefits to the customer relate to non-energy benefits (such as improved health or comfort), and so it might be more appropriate for another funding agency (such as the government) to fund this program rather than utility ratepayers.

There are some nuances with this test:

- **Value of energy saved:** the $/MWh value should be the same as that used in Step One.
- **Free-rider adjustment:** There may be some customers who participate in the energy efficiency program (for example, by receiving a rebate for installing an efficient motor or receiving a subsidized energy efficiency audit), when they would have done this anyway without an

incentive. These customers are referred to as 'free-riders', and the energy associated with estimated free-riders should be deducted from the total energy savings estimated to result from the program.

- **Spillover adjustment:** In this case, a customer undertakes an energy efficiency investment or behaviour change because of an energy efficiency program but does not directly participate in that program. An example could be where an energy efficiency program encourages market transformation such that the more efficient product becomes 'business as usual'. The estimated savings from the energy efficiency program can therefore be grossed up for any spillover effect. For example, in British Columbia utilities are allowed to claim a portion of savings from any code or standards towards which market transformation programs were targeted

If a program passes the utility cost test it demonstrates that it is lower cost for a utility to 'nudge' a customer into changing their behaviour instead of supplying the energy that would otherwise be wasted.

It is important to not discount energy efficiency programs that can have significant benefits (such as advertising or educational programs) just because their energy savings can be hard to measure. Some level of judgement is therefore required. In British Columbia, utilities are required to offer education programs as part of their portfolio of energy efficiency offerings. Other effectiveness considerations in putting together a portfolio include minimizing 'missed opportunities' and maintaining customer and trade relationships.

Lost opportunities occur where there is a limited time window to encourage improved customer efficiency (for example, new building construction or factory retrofit), such that if the energy efficiency investment is not made at that time it can be significantly more expensive to undertake later on. It therefore might be appropriate to include higher cost programs in the portfolio targeted at minimizing lost opportunities. Energy efficiency programs can also benefit from building relationships with partners, such as customers, retailers and trade organizations. It can be useful to ensure that the portfolio includes programs that maintain these relationships.

Another consideration in designing energy efficiency programs is to look at the whole system (such as the whole house or factory) rather than individual measures. An example of this is a British Columbia utility's commercial performance program for existing buildings. This includes funding for energy efficiency audits, funding towards the cost of cost-effective capital investments, and additional bonus funding if the customer successfully implements one or more approved conservation measures.

In British Columbia, the cost-effectiveness tests can also be applied at the portfolio level (instead of at the program level). This gives the utility increased flexibility to include 'hard to measure' or higher cost programs in its portfolio.

Other Tests

Other energy efficiency program tests that are often discussed include the participant cost test and the rate impact test. While they are not included in the effectiveness considerations above, they can provide useful information:

- **Participant cost test:** this test measures the payback period to a customer of participating in the energy efficiency program – for example, a lighting program could have a payback period of a couple of years. The participant cost test result can be useful in setting the incentive level (for example, if a customer requires a payback period of 2 years before making an energy efficiency investment, the incentive level could be set to provide this). However, the need for a low payback period to 'nudge' a customer into changing their behaviour could also indicate that other market barriers (such as a lack of time or information) might be a more appropriate target of energy efficiency programs.
- **Ratepayer impact test:** this test identifies whether customers who do not participate in an energy efficiency program will still benefit from other utility customers becoming more efficient. Generally, all customers benefit from energy efficiency programs offered to an unprofitable customer (i.e. where incremental revenues do not cover incremental costs). While a utility can use energy efficiency programs to reduce sales to unprofitable customers, a more appropriate action could be to change the rate design such that incremental sales to the customer at least recover incremental costs.

  The ratepayer impact test is, however, used in British Columbia to evaluate fuel switching programs to 'nudge' customers to switch from fossil fuels (for their cooking, heat, power etc. needs) to cleaner electricity. Utility funded fuel switching programs pass this test when the net income from additional utility sales (revenues less marginal costs) exceeds the utility cost required to obtain them.

BALANCE

The effectiveness considerations above should result in identification of cost-effective energy efficiency programs that 'nudge' customers into reducing their waste of energy.

Assuming the cost of these programs are recovered from all customers through the utility rates, the next step is to ensure that all customers have a reasonable opportunity to participate in them.

This 'Balance' step requires a review of the utility programs by customer group (e.g., residential, commercial, industrial) and/or by region (e.g., rural vs. urban) to ensure that a reasonable level of funding is allocated to each group. Useful metrics to perform this analysis can include energy efficiency spend by customer group as a percentage of group revenue, and energy efficiency MWh savings by customer group as a percentage of group MWh sales. There is no requirement that percentage funding levels are similar for each customer group, however this step will ensure that energy efficiency funding is not just targeted towards the lowest cost customer group.

Balance considerations also require a review of energy efficiency programs to ensure that they include programs specifically designed to target 'hard to reach' customers such as low-income customers and renters. Low-income customers and landlords with tenants who pay the electricity bill are less likely to participate in traditional energy efficiency programs. In British Columbia, there is a requirement that utility energy efficiency programs include programs that specifically target these 'hard to reach' customer segments.

DEALING WITH UNCERTAINTY

It is fairly straight forward to install a meter on a generator to measure the amount of energy generated, but the amount of energy delivered from energy efficiency programs can be harder to measure. This measurement uncertainty can make it harder to obtain funding for cost-effective energy efficiency programs.

The level of measurement uncertainty inherent in energy efficiency programs can, however, be reduced significantly by following established protocols for evaluation, measurement and verification (such as International Performance Measurement and Verification Protocols). If a region does not have expertise in this area training programs may need to be established.

Lack of adequate metering can also result in measurement uncertainty. One way of addressing this is to develop a 'Deemed Savings Manual' which estimates energy savings for installed energy efficiency measures per unit (e.g. efficient light or pump installed). While this takes some coordination and effort up-front, the results can provide relative accuracy on average. An example is California's Database for Energy Efficiency Resources (DEER).

Some level of uncertainty may also be acceptable where the estimated cost of energy efficiency programs is significantly lower than supply side costs.

Another concern that is sometimes levied on energy efficiency programs is that the customer may change their behaviour after making an energy efficiency investment. For example, an industrial customer may increase their production after they improve the efficiency of their equipment, or a residential customer may set their thermostat to a more comfortable level after improving the efficiency of their home.

In addressing this concern, it is important to look at what is driving the increase in consumption and cycle back to the definition of success outlined above. 'Success' is a reduction in waste of electricity, not just less use of electricity. Provided the customer is not wasting this additional electricity consumed, any increase in consumption can be ignored when it comes to evaluating the cost-effectiveness of the program.

However, if the increase in consumption is due to a waste of electricity (for example, the customer installs LED lights but then leave them on when not needed), then this waste should be deducted from the estimated electricity savings.

CONCLUSION

Energy efficiency programs that encourage customers to be more efficient in their use of energy can be a low-cost way of meeting a jurisdiction's energy needs.

It is hoped that this paper will assist organizations secure funding for energy efficiency programs by providing a 'plain English' overview of how we can ensure these programs are cost-effective and address equity concerns around who pays and who benefits

Utilities can also be a valuable vehicle to fund and deliver cost-effective and balanced energy efficiency programs. As noted by a utility energy efficiency expert in Britsh Columbia, "If we can give utilities the mandate to support energy efficiency and the economic driver, they will pursue it."

RESPONSE TO COMMENTS

I am very grateful for each of the external reviewers on the early draft of this paper.

Reviewer 1 asked for greater consideration to be given to challenges faced by utilities in India, such as customer segmentation and how baselines can be set where there is a lack of metering.

For customer segmentation, I have updated the 'Effectiveness – Step Two' section to discuss residential and commercial end-use surveys and the importance of leveraging trade ally networks and community associations to better identify and target different customer segments. I have also discussed a potential approach (deemed savings) to deal with a lack of metering in the 'Uncertainty' section.

Reviewer 2 stated that the paper can be strengthened by describing how this model has evolved over the last few decades; how utilities are dealing with a shift from 'widgets to systems'; and other problems and challenges BC utilities have faced.

I have expanded the 'Introduction' section to describe the evolution of this model and have expanded the 'Effectiveness – Step Two' section to highlight two approaches used to shift from 'widgets to systems' - evaluation on a portfolio (rather than program) basis and building programs that look at the whole building rather individual measures.

A discussion with BC utility energy efficiency experts indicated that key challenges faced by utilities offering energy efficiency programs are: cost-effectiveness tests that do not include all the key benefits (such as emission reductions and non-energy benefits); lack of a financial incentive for the utility to offer energy efficiency programs; and difficulty supporting market transformation programs. I have expanded the discussion of market transformation programs in the 'Effectiveness – Step Two (spillover)' section of this paper to ensure that strategies to address all three of these challenges have been included.

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I would also like to thank Hudson Nock (16 years old) for his review of this paper and suggested changes to ensure it was written in 'plain English'.

DISCLAIMER

This paper does not represent the views or opinions of the BCUC, nor does it express, or intend to express, any opinion on pending or future matters before the BCUC. The analysis and information contained within this paper were compiled personally by the author, and not in a professional capacity as an employee of the BCUC..

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SELECTION OF CHARGING TECHNOLOGY FOR ELECTRIC FOUR-WHEELER COMMERCIAL FLEETS IN THE INDIAN CITIES

Chandana Sasidharan[1], Anirudh Ray[2] ,Shyamasis Das[3]

[1]*Power Utilities and Electric Mobility Alliance for an Energy Efficient Economy,* Delhi, India
chandana@aeee.in

[2]*Department of Physical Planning School of Planning and Architecture,* Delhi, India
anirudhray0004@gmail.com

[3]*Power Utilities and Electric Mobility Alliance for an Energy Efficient Economy,* Delhi, India
shyamasis@aeee.in

ABSTRACT

The paper is concerned with developing an effective and comprehensive framework for the selection of charging technologies for electric four-wheeler (e-4W) fleets in India. Selection of appropriate charging technology is critical for the successful operation of all e-4W fleets. The investigation identifies the six charging possibilities for the four major segments of four-wheeler commercial fleets based on the type of operation. The study examines various e-4W models and categorizes e-4W models in India based on the battery voltage. The paper develops a classification framewok for charging technologies. The paper identifies the plausible charging options separately for low and highvoltage e-4Ws. Subsequently, the study determines the "*best-fit*" charging technology for meeting the charging requirements of the commercial fleet for every charging option using Multi-Criteria Decision Analysis (MCDA). The findings show that DC charging is not essential for all charging cases for e-4Ws, and AC charging is better suited to certain specific situations.The study aims to assist the stakeholders to plan installation the charging stations and in turn accelerate the penetration of commercial electric vehicle segment.

Keywords—electric vehicles, charging technology, electric car, india, MCDA

INTRODUCTION

The commercial passenger and goods delivery fleets are a sweetspot for electrification as echoed by the subsidy support in second phase of the FAME scheme (Ministry of Heavy Industries and Public Enterprises, 2019). Government of India is committed to the promotion of green mobility and is enticingthe commercial fleet operators to convert 40% of their fleet to electric by 2026 (Reuters, 2019). A essential precondition supporting the rapid adoption for electric vehicles for four wheeler commercial segment is deployment of adequate charging infrastructure for the vehicles at suitable locations (Hall, et al., 2018). The charging facility planning should should take into account two key elements:

- Where to charge, i.e., at captive charging facilities, public parking spaces or en-route
- How to charge, i.e., type of charging technology to be adopted

Selection of appropriate charging technology is the an important step for planning deployment of charging faciltiies. There is a lack on clarity on the selection of technology for public charging infrastrucutre. The paper intends to assist with developing an effective and comprehensive framework for the selection of charging technologies for electric four wheeler commercial fleet in India.

Multiple criteria decision making (MCDM) is a versatile technique that is employed in EV charging problems. (Liu, et al., 2018). Selection of suitable locations for charging stations is viewed as a MCDM problem (Karaşan, et al., 2018) (Wu, et al., 2016) (Stojčić, et al., 2019). Evaluation index system with environmental, economic and social criteria is developed for charging station siting using MCDA (Guo & Zhao, 2015). There is hardly any literature on identification of best-fit charging technology. To the best of author's knowledge, this is the first time MCDA is used for selection of charging technology for electric four wheelers. The authors have previously used MCDM for evaluation of charging technology for electric buses (Das, et al., 2019).

4-W COMMERCIAL FLEETS

The commercial fleets can be broadly classified into two segments based on the type of load they carry, *i.e.*,passengers or goods. These segments can be further classified into the following four segments as shown in **Figure 1**.

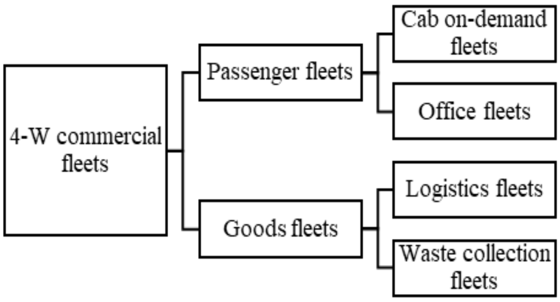


Figure 1: Types of four wheeler commercial fleets

1. **Cab on-demand fleets:**These fleets caters to the mobility demand by linking the public to for-hire drivers generally through an app-based service. These services operate on dynamic routes within an urban area (NITI Aayog, 2018).
2. **Office fleets:** This type of operation involves travel of the employeesbetween their workplaces and residences or other prefixed drop-points. The trips mostlyhave pre-planned routes asfleet operator is aware of the travel demand at specific hours of the day.
3. **Logistics fleets:** These fleets are used for transporting or delivering goods from one point to another in a city and the transactions commonly happen through e-commerce. Often, the operation of these fleets is based on hub-and-spoke model.
4. **Waste collection fleets:** Such fleets are part of the waste management system of a city and the collection of solid waste from the doorsteps of businesses or residences, community bins, solid waste receptacles, etc. and accumulating the waste at a central node, *etc.*.

CHARGING OPTIONS

The charging options categories applicable for the electric fleet segments identified based on the possible locations for charging. The categories for the commercial fleets identified as presented in **Figure 2**, are iterated below.

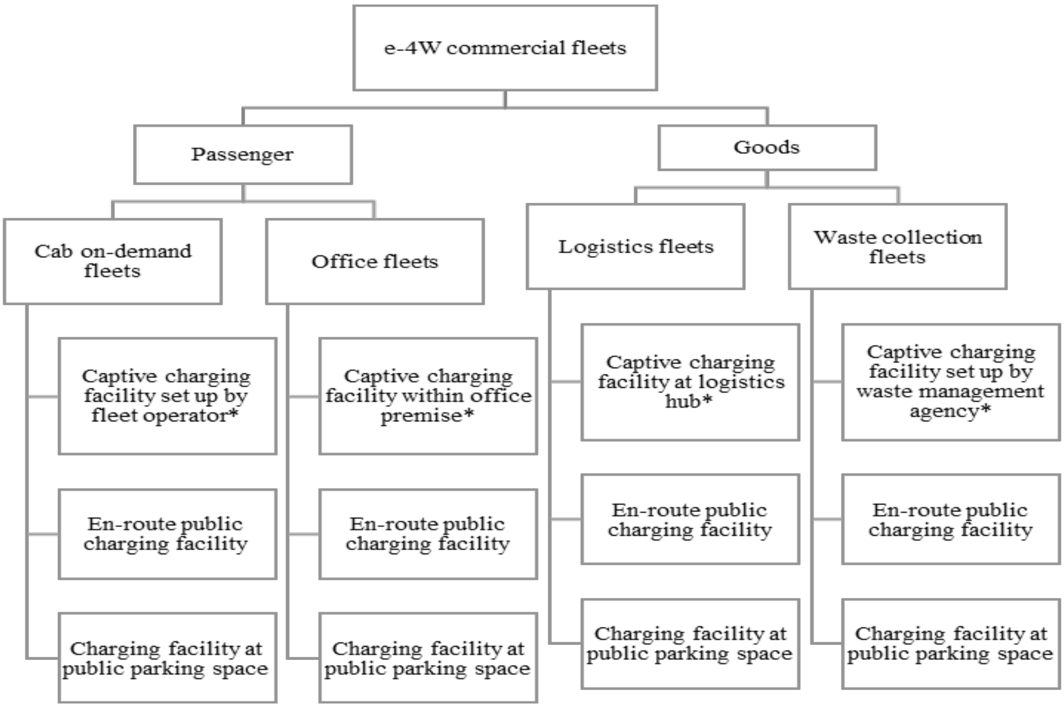
1. **En-route public charging facilities**are the sites located by the sides of the roads. They are similar to regular fuel refilling stations and are open to the public.
2. **Charging facilities at public parking spaces**refer to the parking spaces in public places like malls, business districts, hospitals, schools, community halls, etc. which are equipped with EV chargers or battery swapping systems. These facilities are also open to the public but with restricted access.
3. **Captive charging for cab on-demand fleet** operators are meant for charging (or swapping) the cabs. Here, the charging infrastructure is established exclusively to charge the electric cab fleet of a cab-aggregator.
4. **Captive charging within office premises**are intended for charging (or swapping) electric office cab fleets. This charging facility too is meant for exclusively charging office cab fleet.
5. **Captive charging facilities at logistics hubs** are aimed at meeting the charging demand of e-4W logistics fleets, primarily e-commerce. The parking bays for charging the vehicles are available within the logistics hubs. The charging infrastructure is dedicated for charging exclusively the logistics fleet.
6. **Captive charging for by waste management agencies:** refer to the charging facility set up for captive use by waste collection fleets and located at sites where the solid waste is consolidated at a local level.

E-4W MODELS IN INDIA

The details of the current car models in India is available in annexure Table 6. There is a difference in charging technology associated with the e-4Ws in Indian market. The most distinguishing factor is the battery voltage, as chargers have to suit the battery voltage. Hence this study classifies the electric four wheelers in Indian market to two categories

1. Low Voltage e-4Ws- which has a battery voltage under 120V
2. High voltage e-4Ws- which has a battery voltage greater than 120 V

There are two notable differences between charging options of these two cars. First the the popular DC charging protocols of Combined Charging System (CCS) or Charge de Move (CHAdeMo) is not applicable to the Low Voltage cars. Secondly, the on-board charger power of the Low Voltage cars is lower than the High Voltage cars. Hence the planning of charging facilities for e-4Ws in India needs understanding of charging technologies which is presented subsequently.



** Charging facility established within a semi-restricted premise for commercial or non-commercial purpose for charging of e-4Ws. The chargers are available to any e-4W for charging.*

Figure 2: : Possible charging facilities for different commercial electric four-wheeler segments

CHARGING TECHNOLOGIES

Charging technologies currently deployed worldwide for charging e-4Ws differ in their method of electricity transfer, power output levels, etc. (IEA, 2018). Any e-4W can be charged by conductive AC charging technology if it has an on-board charger. DC charging is performed when charger is not on-board on the e-4Ws. Conductive AC and DC charging is categorised into three levels: Level 1, Level 2 and Level 3 (refer to Table 1) considering the common service voltages and power levels. AC Level 2 (AC-II) is subclassified into two classes based on charging power. Class a (AC-IIa) charging is a simple plug and play charging using a 16A plug outlet and chargers on board the EV. AC-IIb charging is possible for the newer car models which has on-board chargers rated at higher power levels which a domestic 16 A socket cannot provide.

Bharat AC 001(BAC) and Bharat DC 001(BDC) are special type of chargers based on the corresponding Indian standard (DHI, 2017). Bharat AC 001(BAC) is a special type of AC Level 2 charger with a three-phase input and a single-phase output. Bharat DC 001 (BDC) is a special category of charger which is specifically designed at an output voltage level suitable for charging the existing Low Voltage e-4W models in India.

Based on the practicality-assessment (as summarized in **Table 1**1), it is found that:

- Battery swapping is not a common technology in practice for charging of e-4Ws. Only select car models from Renault, NIO and Tesla are designed with swappable batteries (Hall, et al., 2018). The high cost of installation and operation and the requirement for significant modifications of the vehicle-design are some of the major hurdles in its implementation.
- Inductive charging has achieved only limited success as a home charging solution primarily due to high costs. (Hurst, 2018). The inductive charging solutions for public charging are at the nascent stage (Shepard & Jerram, 2018).
- AC Level 3 (AC-III) charging is not shortlisted as the current and upcoming EV models do not have three phase on-board chargers (Spöttle, et al., 2018).
- DC Level 3 (DC-III) chargers of 175 kW are new in the market, but not suitable for existing EV models in India (Kane, 2019).

This study has shortlisted the plausible charging technologies for public charging facilities. These are AC-II, Bharat AC 001, Bharat DC 001, DC-I, and DC-II charging.

Table 1: Comparison of charging technologies

PARAMETERS	AC – IIa	AC – IIb	BAC	AC – III	BDC	DC -I	DC-II	INDUCTIVE CHARGING	BATTERY SWAPPING
Input voltage from grid (V)	230[b]	230[b]	415[b]	415[b]	415[b]	415[b]	≥415[b]	≥230 [b]	≥415[b,c]
Rated output power of charger (kW)	1.6 - 3.3[e]	3.3 - 7.3[f]	10[g]	11 - 43[h]	10 - 15[g]	≤50[h]	>50[h]	3.3 - 7.2[i]	data not available[c]
Output voltage from charger[h] (kW)	230	230	230	415	48/ 60/ 72	50-500	150-950	230[i]	data not available[c]
Maximum output current[h] (A)	16[e]	32[e]	15	63	200	80	200	30[i]	data not available[c]
Output power of charging technology considered for analysis (kW)	3.3[k]	6.6[j]	3.3[k]	22[l]	10[k]	25[l]	50[l]	7.2[i]	data not available[c]
Charging/ swapping time for HV e-4Ws in hours[m] (battery rated 40 kWh)	14-20	4-6	8-12	1.3-1.8	1.3 - 2	1.1-1.6	0.6-0.8	4-6	5 minutes[n]
Charging/ swapping time for LV e-4Ws in hours[m] (battery rated 15 kWh)	7-10	na	4-6	na	1.4-2	na	na	na	na
No. of EVs that can be charged from an EVSE at a time	1	1	3	1	1	1	1	1	1
Electricity connection required[o] (HT/ LT)	LT	LT	LT	LT	LT	LT	HT	LT	HT
Capital cost of charging technology [q](₹)	0 - 24,000	45,000 - 65,000	60000 - 1,00,000	80,000 - 1,20,000	2,60,000	10,00,000	50,00,000	91,000 -2,10,000	3,50,00,000- 14,00,00,000
Cost of ancillary infrastructure (₹)	1,400-1,900	1,600-2,500	1,800-2,500	4,000-11,000	2,800-3,500	8,000-15,000	6,25,000- 8,25,000	1,600-2,500	2,50,000 – 4,00,000
Area requirement (m^2)	not applicable	0.2 (wall mounted)	0.2 (wall mounted)	0.15 (wall mount)	0.8 (wall mount)	0.4 (wall mount)	1-1.5	not applicable	not available
Ease of drawing electricity from the distribution network	Not difficult	Not difficult	Not difficult	Moderately difficult	Moderately difficult	Moderately difficult	Difficult	Not difficult	Difficult
Established precedence for charging e-4Ws	yes	Yes	Yes	Yes	yes	yes	yes	Limited[r]	Limited[s]
Suitability for installation in public charging facilities in India	yes	yes[s]	Yes	No	yes	yes	yes	no	limited

[b] Voltage set at the common single-phase and three-phase AC distribution in India
[c] Depends on both charging point for battery and the swapping infrastructure
[d] Power range set considering 12-20A input current range specified in NEC (Morrow, et al., 2008)
[e] Power range set considering 16A input current range for a domestic socket in the Indian context
[f] Power range set considering 32A input current range for a single-phase circuit in the Indian context
[g] Output power of Bharat AC 001 and Bharat DC 001 (DHI, 2017)
[h] As per specifications of e-4W chargers currently available in the market
[i] Output power of wireless chargers currently available in the market (WiTricity Corporation, 2018) (WiTricity, 2016) (Evantran, 2019)
[j] Highest possible power considered at power factor 0.9
[k] Output power set according to DHI guidelines (DHI, 2017)
[l] Assumed based on the study of chargers in the market (Spöttle, et al., 2018)

[n] Swapping time set based on available details
[o] Connection requirement is assessed as per India's grid code
[p] Requirement assessed based on industry accepted standards
[q] Costs are estimated based on available literature and market values (Spöttle, et al., 2018) (Shepard & Jerram, 2018) (EVConnectors, 2019)
[r] Few successful commercial use-cases have been reported for inductive charging and battery swapping for e-4Ws
[s] High-power single-phase charging may lead to unbalance in the distribution network.

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METHODOLOGY

These shortlisted technologies are further examined to select the best-fit against a charging requirement of an e-4W fleet in India. Taking into cognizance the possible complexity to pinpoint the best-fit technology for charging of e-4W commercial vehicles, the study develops a composite Multi-Criteria Decision Matrix (MCDM) for a type of public charging facility. A MCDM consists of a set of techno-economic parameters, each assigned a weight based on the assessed degree of importance using the following scale (refer to Figure 3).It must be noted that the MCDMs for the low-voltage and the high-voltage e-4Ws have to be separate, owing to the fact that the low-voltage e-4Ws can only be charged with BAC, AC-II(A) or BDC chargers. The study shortlists the plausible charging technologies for Low voltage and High voltage e-4Ws as shown in Table 2.

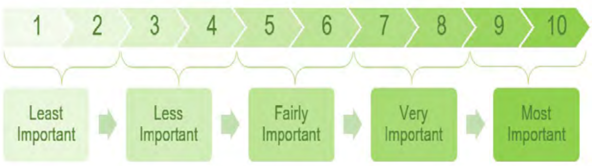

Figure 3: Scale for assessing importance of a parameter

Table 2: Plausible charging technologies for HV and LV e-4Ws

PLAUSIBLE CHARGING TECHNOLOGIES	E-4W CATEGORY	
	HV	LV
AC Level 2-a	Yes	Yes
Bharat AC 001	Yes	Yes
AC Level 2-b	Yes	No
Bharat DC 001	No	Yes
DC Level 1	Yes	No
DC Level 2	Yes	No

An example of application of MCDM to identify the "best-fit" charging technology for LV and HV e-4W en-route public charging facilities is showcased below. The MCDM in **Table 3** shows that Bharat DC 001 gets the highest normalised weighted rank, making it charging technology is most suitable for low-voltage e-4W en-route public charging. Similarly, the MCDM for high-voltage e-4W presented in Table 4 shows that DC Level 2 is the most suitable charging technology. The details of the weights assigned for the technical and economic parameters en-route charging is available in annexure table 7.

Table 3: Multi-Criteria Decision Matrix for en-route public charging for low-voltage e-4Ws

Parameters	Criteria	W	BAC		AC-II (A)		BDC	
			R_{BAC001}	$W*R_{BAC001}$	$R_{AC\text{-}II(A)}$	$W*R_{AC\text{-}II(A)}$	R_{BDC001}	$W*R_{BDC001}$
TECHNICAL	Charging time	10	1	10	1	10	3	30
	Land requirement to set up a charging facility	10	1	10	1	10	3	30
	Ease of drawing electricity from the distribution network	5	1	5	3	15	1	5
ECONOMIC	Capital cost per charger	8	2	16	3	24	1	8
	Cost of electricity for charging an e-4W by an EVSE	6	3	18	3	18	3	18
-	Sum	39	59		77		91	
	Normalized Weighted Ranks		1.51		1.97		2.33	

W = Weight of a criterion for a particular charging requirement of a specific vehicle segment

R = Rank of a charging technology against a particular criterion

The charging technology which notches up the highest normalised weighted rank would qualify as the most preferred option. The least normalised weighted rank would determine the least preferred optio

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Table 4: Multi-Criteria Decision Matrix for en-route public charging for high-voltage e-4Ws

Parameters	Criteria	Weight	Bharat AC 001		AC - II (A)		AC - II (B)		DC Level 1		DC Level 2	
			R_{BAC001}	W^*R_{BAC001}	$R_{AC-II(A)}$	$W^*R_{AC-II(A)}$	$R_{AC-II(B)}$	$W^*R_{AC-II(B)}$	R_{DCL1}	W^*R_{DCL1}	R_{DCL2}	W^*R_{DCL2}
TECHNICAL	Charging time	10	1	10	1	10	3	30	4	40	5	50
	Land requirement to set up a charging facility	10	1	10	1	10	3	30	4	40	5	50
	Ease of drawing electricity from the distribution network	5	3	15	5	25	4	20	2	10	1	5
ECONOMIC	Capital cost per charger	8	4	32	5	40	3	24	2	16	1	8
	Cost of electricity for charging an e-4W by an EVSE	6	2	12	2	12	2	12	2	12	1	6
	Sum	39	79		97		116		118		119	
	Normalized weighted ranks		2.03		2.49		2.97		3.03		3.05	

W = Weight of a criterion for a particular charging requirement of a specific vehicle segment

R = Rank of a charging technology against a particular criterion

The charging technology which notches up the highest normalised weighted rank would qualify as the most preferred option. The least normalised weighted rank would determine the least preferred option

CONCLUSION

The study aims to assist the stakeholders to plan installation the charging stations and in turn accelerate the penetration of commercial electric vehicle segment. The effectiveness and feasibility of deployment and use of a charging technology hinge on a range of factors, both technical and economic. On the one hand, the technology should be suitable to satisfy the criteria for charging the vehicle (e.g. charging time) and on the other, its establishment and operation should be cost-effective.

The paper identifies that a total of six charging options exist for the four categories of electric four wheeler commercial fleets. The paper also provides a relevant details of the charging technology before determining the best fit charging technology. The paper finds that it is important to evaluate the suitability charging technology only with effective consideration to the current type of 4-eWs.

The study also classifies the e-4Ws in India to two classes based on the battery voltage. Further the techno-economic parameters are used in designing seperate MCDMs for High Voltage and Low Voltage e-4Ws. The results from MCDM considering both techno and economic parameters for the six identified charging facilities is presented in **Table 5.** The results show that for fleet operation of High Voltage EVs charging at DC Level 2, AC Level 2 (A) and AC Level 2 (B) are the best fit technology. On the other hand for Low Voltage cars both AC Level 2 (A) and Bharat DC 001 are suitable options.

It is worthwhile to remember that the weights (refer to Tabe 7) assigned to the 'high-impact' technical and economic parameters considered in the composite MCDMs vary with the use case of public charging facility. This is inevitable as the criteria to evaluate *"best-fit"* also change. For instance, charging time may be the most important consideration in case of a charging facility that caters to time-bound business operations. On the other hand, best practices for battery management may involve a selection mix of slower and faster charging practices.

Subject to the limitations, the results show that it is possible to bring in objectivity for selection of charging technologies for four wheeler commercial vehicles. The study recommends 3.3 kW AC Level 2 AC chargers for public parking facilities.10 kW Bharat DC 001 chargers and 50 kW DC Level 2 chargers will suit requirements for en-route charging and cab on demand fleet charging faciliites for Low voltage and High voltage e-4Ws respectively. Alternately, in office premises, logistics hubs and waste management hubs 7.4 kW or 3.3 kW AC chargers may be installed. It is important to note that these results may change with the cost of chargers and with the corresponding evolution in charging technology such as with the availability of AC-III, or DC-III chargers for e-4Ws.

Table 5: Summary of MCDM results fore-4Ws

CHARGING FACILITY TYPE	HIGH VOLTAGE EV	LOW VOLTAGE EV
En-route public charging facility	DC Level 2	Bharat DC 001
Charging facility at public parking space	AC Level 2 (A)	AC Level 2 (A)
Captive charging facility for cab on-demand fleet	DC Level 2	Bharat DC 001
Captive charging facility within office premise	AC Level 2 (B)	AC Level 2 (A)
Captive charging facility at logistics hub	AC Level 2 (B)	AC Level 2 (A)
Captive charging facility for waste collection fleet	AC Level 2 (A)	AC Level 2 (A)

ANNEXURE

Table 6: Details of e-4W available in Indian Markets

MANUFACTURER	MODEL	RANGE (KM)	BATTERY RELATED		MAXIMUM CHARGING TIME	MINIMUM CHARGING TIME
			KWH	V	MINUTES	MINUTES
Mahindra [a]	e2o+	140	15	54	440	95
Mahindra [a]	e2o+	110	11	54	360	-
Mahindra [a]	e-Verito	181	21.2	72	690	90
Mahindra [a]	e-Supro	112	14	72	510	-
Tata [b]	Tigor	213	21.5	72	360	180
Hyundai [c]	Kona	452	39.2	350	1140	57

a. Source : https://www.mahindraelectric.com/vehicles
b. Source: https://tigor.tatamotors.com/electric/specification
c. Source: https://www.hyundai.com/in/en/find-a-car/kona-electric/features

Table 7: Ideal values and weights of techno-ecomonic parameters of MCDM for decision making

S. NO.	PARAMETER	IDEAL VALUE	JUSTIFICATION OF THE IDEAL VALUE	WEIGHTS USED FOR MCDM ANALYSIS					
				En-route	Public Parking	Captive cab on demand	Captive office premise	Captive logistics hub	Captive waste managemen t
1.	Charging time	36 minutes for HV 84 minutes for LV	Minimum time required to charge the battery	10	6	9	6	7	6
2.	Land requirement to set up a charging facility	Minimal	Area requirement is preferred to be as low as possible.	10	5	10	5	5	5
3.	Ease of drawing electricity from the distribution network	Not difficult	The ease of drawing electricity depends on: the ability to cater to charging requirement without needing an 11/ 33 kV connection	5	7	5	5	5	8
4.	Capital cost per charger	Minimum cost	This range has been considered taking into account the minimum price of suitable EVSE	8	9	7	8	8	8
5.	Cost of electricity for charging an e-4W by an EVSE	Minimum cost	The charging system which should attract the lowest energy charges	6	8	6	6	7	7

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EVALUATING THE CHALLENGES FACED BY SHS AND DRE PRACTITIONERS IN ENERGY EFFICIENT APPLIANCES MARKET OF INDIA

Srishti Sharma[1], Bhawna Tyagi[2]

[1]*Alliance for an Energy Efficient Economy*
Delhi, India
srishti@aeee.in

[2] *Alliance for an Energy Efficient Economy*
Delhi, India
bhawna@aeee.in

ABSTRACT

Despite the interventions to boost electrification in India, rural areas continue to face the challenge of limited or unreliable access to grid power. In providing energy access, energy efficiency can play a crucial role. Energy efficiency will facilitate rural households to use multiple appliances and improve their quality of life with many co-benefits. Household equipped with energy efficient (EE) appliances will consume less energy than normal appliances. The EE appliance market in rural areas is not fully developed in India to its potential as compared to countries like Bangladesh, Kenya, Uganda, Tanzania, and others.

Solar Home System (SHS) and Distributed Renewable Energy (DRE) practitioners are playing a key role in making these EE appliances available to rural India by working at the grassroot level. They provide solutions that are a combination of off-grid power and EE appliances. However, these practitioners face numerous challenges in deploying their services and solutions. To study these challenges, study collected data from practitioners selling these efficient appliances through primary survey. The paper identified lack of consumer awareness as one of the crucial factors impacting appliance penetration in the rural market followed by consumer affordability and market competition. To overcome these challenges, different stakeholders could play different role. There is need to deploy strategies to create awareness among consumers, promote research and development and ensure availability of easy financing options for both consumers and manufacturers. The insights from the paper will enable policymakers and organisations working in this domain to bring significant transformation in the energy efficient appliance market.

Keywords— Solar Home System (SHS), Distributed Renewable Energy (DRE), off-grid, Energy Efficiency, Energy Access

INTRODUCTION

Energy is a strategic commodity which is critical to the development and prosperity of an economy. There is a strong relationship between energy and economic output which has been validated by several studies [Asongu, Montasser, and Toumi (2015); Palamalai, Ravindrab and Prakasam (2015); Saidi and Hammami (2015)]. According to Economic Survey (2019), one gigajoule increase in per capita energy consumption translates into USD 145 increase in per capita GDP of an economy. Despite home to 18 per cent of world population, share of India in world's primary energy consumption is only 6 per cent. India's per capita energy consumption is one third of the global average of 18 tonnes of oil equivalent (Economic Survey, 2019). To persevere on the high growth path and meet the aspiration of its citizens, India needs to quadruple its per-capita energy consumption (Economic Survey, 2019).

Access to affordable electricity for each and every household is a necessary condition for social and economic development. Energy access is the "golden thread" that weaves together economic growth, human development and environmental sustainability (IEA, 2018). Sustainable Development Goal (SDG) on affordable and clean energy has interlinkages with all other SDGs. This is substantiated by strong relationship between per capita energy consumption and Human Development Index (HDI), especially at low levels of energy consumption. Despite being fastest growing economy, India ranks 130 out of 189 countries in HDI ranking with HDI value of 0.64 in 2017 (UNDP, 2018).

Energy poverty is more pervasive than income poverty in India. There is even wide disparity between rural and urban areas in terms of energy access. To ensure rural electrification, Government of India (GoI) is undertaking various measures from last one and a half decades such as Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY), Saubhagya Scheme, among others. According to Saubhagya scheme, almost all the rural households are electrified till date and only 0.01% are left un-electrified. However, the success of rural electrification should not be measured only on the basis of connections provided, but also on the basis of provision of reliable and quality power supply during peak hours (Chaudhury and Tyagi, 2018). According to Rajya Sabha Data (2018), around 21.7 per cent i.e. 3.9 crore of rural households are still un-electrified, out of 18.1 crore total rural households. Therefore, achievement of 100% energy access along with reliable power supply continues to be a challenge in India.

To achieve this target, it is important to follow a sustainable development model which focuses on reducing energy intensity[1]. One of the sustainable ways to approach the challenges of energy access is through energy efficiency measures that allows to use less energy to produce same output and still save energy to provide to more people. In case of India, energy intensity started declining at per capita GDP of USD 578 since 1991 compared to US whose primary energy intensity started declining at USD 23,309 from 1970 onwards (Economic Survey, 2019). Energy saving potential from energy efficiency measures for India estimated to be around 7.21 per cent of net electricity consumption in 2017-18 (Economic Survey, 2019). As a result, energy efficiency is a key resource for energy access. However, the contribution of energy efficiency in energy access has been often overlooked.

One of the ways to tap into the benefits from end-use energy efficiency is by using energy efficient appliances in the low income urban and rural homes. According to Global LEAP Report (2016), Solar Home Systems (SHS) equipped with efficient appliances would use 75% less energy than SHS with normal appliances. The efficiency of appliances has been increasing over the years. The power ratings of appliances by 2020, is predicted to be: 12” table fans - 8 watts, 19” televisions – 10 watts and 100-litre refrigerators – 30-40 watts. Energy efficient appliances in a rural household will facilitate the use of multiple appliances with same or less power supply. This will contribute towards improvement in their quality of life with associated co-benefits. However, energy efficient appliance market in rural India is not developed to its full potential as compared to other countries like Bangladesh, Kenya, Uganda, Tanzania, and others. Thus, the time is ripe to utilize the opportunity of increasing energy access using energy efficient appliances as a resource.

To facilitate the penetration of energy efficient appliances in rural India, Solar Home System (SHS) and Distributed Renewable Energy (DRE) practitioners are playing a key role by working at the grassroot level. They provide solutions that are a combination of off-grid power and energy efficient appliances. As the systems offered by the practitioners to a rural household are small (varying from 10W to 10 kW), they need to explore energy efficient variants of appliances which can be used on these smaller systems, for enabling maximum utilization with limited power supply. However, these practitioners face numerous challenges in deploying their services and solutions. In this light, the present study aims to identify and evaluate the gaps in penetration of these efficient appliances, in the appliance market and explore ways to circumvent them in future.

Literature Review

The role of Energy Efficiency in energy access has been under explored in India. There are only few studies which have looked into the access of off-grid appliances to the rural end-consumers and finding solutions to the associated challenges. Global Leap in their 2016 report ‘The State of the Off-Grid Appliance Market’ focused upon the status of appliance market, prevailing market trends and potential opportunities. The report has highlighted the challenges related to consumer financing and access to low-quality products in the Indian off-grid market. The study with respect to these challenges has recommended the need for partnership with MFIs, availability of financing mechanisms for end-consumers specifically in the off-grid or remote regions and implementation of product’s quality control guidelines. However, the

[1] Energy Intensity is a measure of energy inefficiency of an economy.

study examined the problem from consumer point of view instead of manufacturer or practitioners.

Prayas studied the potential savings from using energy efficient appliances in the Indian households (Boegle, Singh and Sant, 2011). They studied the composition of energy consumption in India and then estimated the potential of savings from efficient appliances. In another study, Prayas focused on selected super-efficient appliances penetration in Indian market and their potential savings (Chunekar et al., 2011). In a policy brief, CEEW and ISEP stated that policy support is required to address the challenges related to affordability and availability of off-grid systems and appliances in rural areas with unreliable electricity supply (Leong, Rupelian and Jain, 2018). However, the studies have not dealt with challenges faced in supplying those efficient appliances in the market.

There are studies which examined the challenges faced by end-consumer and role of SHS and DRE systems in providing access to electricity. Recent report by Brookings emphasized on the challenges faced by end-consumer who rely on mini and micro grids/DRE system for reliable electricity supply (Tongia, 2018). The report has highlighted the issues such as last mile connectivity, high cost of micro-grids, sizing of micro-grid, translating system design between energy (kWh) and capacity (kW), etc. Study also suggested recommendations such as data related to electricity supply should be made available to the public, smart metering payment flexibility for end-consumers and requirement for cross-subsidy mechanisms. Another study also focused on challenges faced in increasing energy access through micro-grids (Institute for Transformative Technologies, 2016). They have also highlighted similar challenges such as cost of micro-grids, limited usability of storage units due to associated technological challenges, high cost of smart meters, etc. To overcome these challenges, study suggested development of an integrated approach consisting of innovative technologies, financial support from private sectors and incentives to the rural household for community electrification. However, none of the studies dived deep into integration of off-grid system with efficient appliances.

The existing studies have primarily focused upon identifying issues and suggesting recommendations to overcome the problems faced by rural community due to the lack of access to reliable grid power, technological challenges associated with installation of off-grid system, and lack of financial support to end-consumers for installing DRE/SHS system. None of them have taken into considerations the perspective of SHS & DRE practitioners, which plays a key role in providing efficient and effective solution to the rural community i.e. a combination of off-grid power and energy efficient appliances.

Therefore, this study attains significance as it focusses upon identifying and evaluating the challenges faced by SHS & DRE practitioners in the appliance market and suggest recommendations to circumvent them in future. The findings will complement the existing studies by providing information on supply side challenges in the energy efficient appliance market. This will enable the policymakers in informed decision making to facilitate penetration of efficient appliances in Indian rural households and small businesses by providing holistic information.

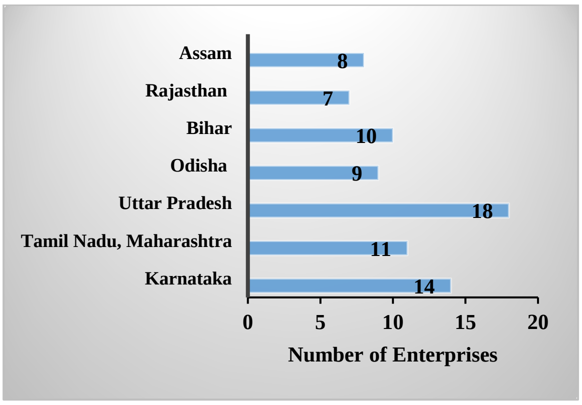
METHODOLOGY

To evaluate the challenges and gaps in penetration of energy efficient appliances, study conducted primary survey of SHS and DRE practitioners in India. The objective was to collate data from the SHS and DRE practitioners providing appliances along with their off-grid systems. The questionnaire included both quantitative as well as qualitative questions and both closed and open-ended questions were asked based on study objectives. The questionnaire was designed to collate information on type of service provider, areas of operation, appliance offerings, challenges, units sold in last three years, factors impacting the sale, among others. The survey was conducted through emails, in-person interviews and telephonic conversations. 389 SHS and DRE practitioners were reached out through questionnaires. In order to avoid biasedness, study sample included both small, as well as large players working in this domain. Out of 389 practitioners, responses were received from 49 which approximately accounts for more than 65 per cent of total market share. The results of the data analysis are discussed in the subsequent section.

DISCUSSION AND RESULT ANALYSIS

The data showed that most of the practitioners are working in the areas of Uttar Pradesh followed by Karnataka, Tamil Nadu, Maharashtra and Bihar as shown in **Figure 1**. SHS and DRE practitioners are finding states like Odisha and Assam as next potential areas for exploring new business opportunities. Majority of the key players (such as Boond, Oorja, OMC Power, SoULS, among others) continue to focus on Uttar Pradesh as out of 3.9 crore un-electrified household 1.4 crore lies in Uttar Pradesh (Rajya Sabha Data, 2018). Karnataka and Tamil Nadu are also favoured as experimental ground for off grid interventions with key stakeholders such as SELCO which are working closely with local communities to converge energy and development goals.

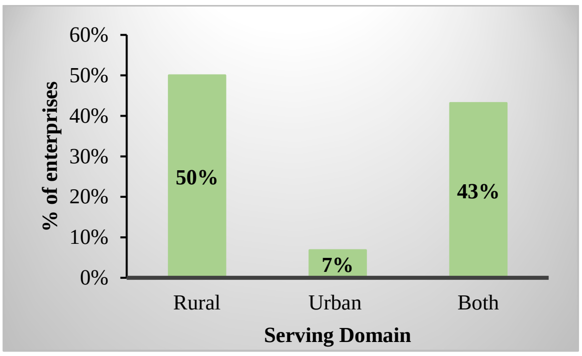
Figure 1: Areas of Operation



Source: Own Calculation

More than 50% of practitioners are serving to rural areas as shown in **Figure 2**. In rural areas, majority of the business opportunities are through households' channel. It is interesting to note that business opportunities through small business are also emerging in rural geography. Providing basic lighting and productive end use infrastructures to small shops are enabling extra income generation opportunities to under privileged communities. In case of urban areas, majority of practitioners are serving both the household and small business consumers.

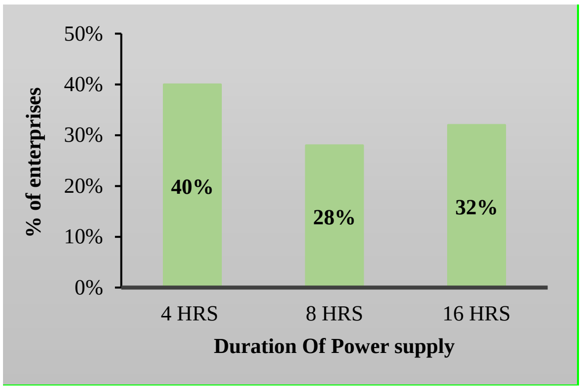
Figure 2: Areas of Operation: Rural and Urban



Source: Own Calculation

In terms of grid supply, practitioners are majorly catering to the areas where grid supply is available for about 8-16 hrs per day as shown in **Figure 3**. However, it is equally important to notice that 40% of practitioners that participated in the survey are still operating in the areas where power availability is less or equal to 4 hrs per day. The states that lie in the category of power supply 4-8 hrs a day are Uttar Pradesh, Bihar, Jharkhand, Orissa, Madhya Pradesh and Assam. The information on hours of supply enables practitioners in bundling the energy efficient appliances together depending on the power availability.

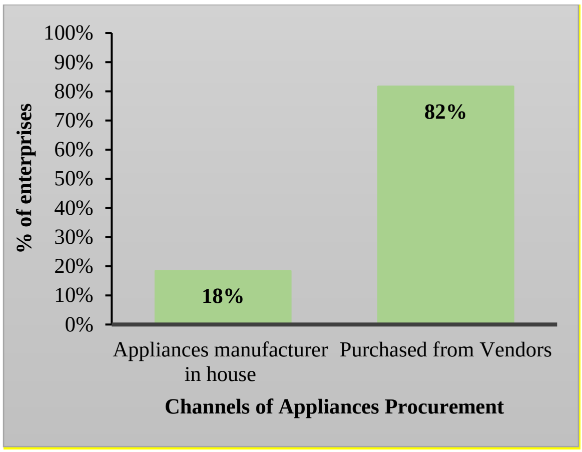
Figure 3: Areas of Operation based on duration of power supply



Source: Own Calculation

Majority of the enterprises (SHS & DRE) are sourcing their appliances from Original Equipment Manufacturers (OEMs) as shown in **Figure 4**. It can be noted that most of the enterprises are system integrators and procuring the appliances they are offering in the markets from two to three vendors.

Figure 4: Procurement of Appliances

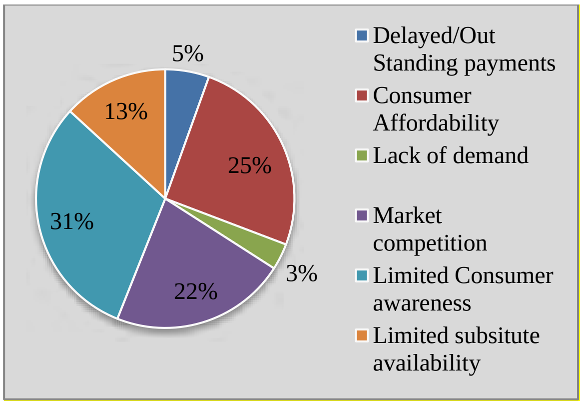


Source: Own Calculation

The study analysed the data on challenges faced by practitioners in selling the energy efficient appliances in the market as shown in **Figure 5**. The practitioner does not foresee lack of demand as a hindrance in appliance penetration rather lack of consumer awareness. About 31 percent of practitioners are facing challenge of consumer awareness followed by consumer affordability and market competition in selling off their appliances. Consumer awareness is critical as practitioners are majorly catering to the households in the rural areas. Many times, consumers are not aware about the type of appliances they require other than lighting and mobile charging. This is true especially in case of productive appliances. In one of the field visits to rural areas, it has been observed that some of the practitioners are deploying innovative strategies to create awareness through various means such as appliance display through mobile vans, live demonstration of appliances, providing customised products, and provision for 15 days trial period to make them aware about the appliances.

Another challenge highlighted by the practitioners is consumer affordability. In rural areas, consumer find it difficult to purchase the appliances offered by the practitioners. Third challenge of market competition is also associated with consumer affordability. The proportion of households who have the purchasing power to buy these appliances are low as a result practitioner compete amongst themselves for a very small share of market. Although, the share of households requiring these appliances, from this market is large.

Figure 5: Challenges faced by SHS/DRE Practitioners



Source: Own Calculation

One of the astounding results is that only 5 percent of the practitioners highlighted the challenge of delayed and outstanding payments in selling the appliances. This implies the positive intention of the consumer to pay back for the appliances purchased. These results are in line with the observation from the field visits that energy efficient appliances allows consumers to use more with limited supply and increase their productivity and income.

RECOMMENDATIONS

There are several recommendations which can be drawn based on our data analysis to address the challenges faced by practitioners in energy efficient market. The recommendations have been classified broadly in three categories based on type of associated stakeholder:

Practitioners

Lack of knowledge and information is observed to be a major challenge faced by practitioners when it comes to the acceptance of new technology and its usage. Hence, there is a strong need for creating awareness and demonstration drives amongst end-consumers of these off-grid systems and appliances, in order to sensitise them about their relevance, functionality and maintenance for a self-reliant system.

Providing free trials of appliances to the consumer could be one of the strategies which could help the consumer in gaining the trust in the technology. This approach has been successfully deployed by SELCO foundation in case of Karnataka. This will enable consumer to get familiarize with the product and will reduce the rigidity in their adoption. Practitioners can draw from the successful case studies of the practitioners of other regions. Before venturing into new area, it is also important to examine the requirements of consumers in terms of hours of supply, appliance requirement, income profile, etc.

To establish a strong network and supply chain, practitioners could collaborate with local NGOs or private players with already existing market linkages at grassroot level. Also, an enterprise/practitioner could involve local residents as the part of their business model. This person shall act as goodwill ambassador as community members will trust that local resident more than an outsider practitioner. Further, the growth and availability of local manufactures and vendors could also help in minimizing the logistics and procurement cost.

Policymakers

The market for off-grid energy efficient products other than lighting is still in its nascent stage. One of the critical challenges faced by practitioners is consumer affordability. Therefore, it requires incentives to grow and flourish. One of the ways to reduce the cost is bulk

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procurement as was done previously by EESL in case of LED programme. To implement this, it is important to identify the next set of appliances which will be demanded by the consumers.

BLDC motor are more efficient than AC motor. However, their adoption in appliances is less due to high cost of BLDC motor. Government could subsidise the production of BLDC motors which will significantly reduce the energy requirement of appliances using these efficient motors. Government support is also required in terms of setting up standards for quality and performance of the product which are both AC and DC. After the product becomes mainstream, development of efficiency rating specifically for the DC appliances and strengthening or revision of already existing efficiency rating scheme becomes relevant.

As the practitioners selling these appliances faces challenge of consumer affordability, compliance with GST will further increase the cost of the product. Therefore, GST compliance should be relaxed for practitioners working in the off-grid market. Also, in order to avoid duplication of efforts and resources, government could maintain data repository of SHS and DRE practitioners with their product offerings and areas of operation. This will help practitioners to collaborate and reduce duplication of efforts. There is also need to support research and development. Technical support and hand-holding will provide support to the SHS and DRE practitioners to convert innovative ideas into action, which will eventually lead to an increase in availability of different type of off-grid appliance.

Financial Institutions

The role of financial institution is crucial both at demand and supply side of appliances. On the demand side, challenge of consumer affordability which is linked to market competition amongst practitioners continues to persist. This is also highlighted by data collected from practitioners. Thus, the process of getting financing needs to be smoothened for rural consumer with less paperwork. If feasibility of particular productive appliance is established in a particular area, then that information needs to be circulated among other banks and branches, to reduce the time period of lending process. Centralised repositories of such case studies need to be developed which should be referred while approving loans in the rural areas. Support from financial institutions and MFIs like Rural Grameen Bank, NABARD and other local financial institutions is required to provide initial support to the small SHS & DRE players in the market.

CONCLUSION

Access to affordable electricity for each and every household is crucial for social and economic development. Rural areas continue to face the challenge of no or irregular supply of electricity. To achieve the target of 100 per cent rural electrification, energy efficient appliances could play a vital role. Presently, the energy efficient appliance market is in its nascent stage. SHS & DRE practitioners are playing a key role by providing solutions that are a combination of off-grid power and energy efficient appliances. However, these practitioners face numerous challenges in deploying their services and solutions.

Majority of the practitioners are catering to rural areas with power supply of more than 8 hours. They are majorly catering to the need of households followed by small businesses. In term of challenges, practitioners does not foresee lack of demand as a hindrance in appliance penetration rather lack of consumer awareness followed by consumer affordability and market competition. Consumer awareness is critical as in many cases, consumers are not aware about the type of appliances they require other than lighting and mobile charging.

To overcome these challenges, different stakeholders could play different role. Practitioners could create awareness among consumers by deploying innovative strategies such as appliance display through mobile vans, live demonstration of appliances, etc. To establish a strong network and supply chain, practitioners could collaborate with local NGOs or private players with already existing market linkages at grassroot level.

Another challenge faced by practitioners is consumer affordability. To address this challenge, policymakers could identify the appliances with maximum penetration potential and could reduce their cost though bulk procurement. Government could also subsidise the production of BLDC motors which will significantly reduce the energy requirement of appliances using these efficient motors. In order to avoid duplication of efforts and resources, government need to maintain data repository of SHS and DRE practitioners with their product offerings and areas of operation. This will help practitioners to collaborate and reduce duplication of efforts. Financial institutions could play crucial role by providing easy financing both at supply and demand side. One of the ways to approach this issue is centralised repositories of successful case studies which should be referred while approving loans in the rural areas. Overall, these stakeholders could play a crucial role in utilising India's energy efficiency potential by contributing the need of energy access in rural India.

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PROSPECTS FOR PV RECYCLABILITY AND THE ASSOCIATED END-OF-LIFE MANAGEMENT; AN INDIAN PERSPECTIVE

Jaideep Saraswat[1], Mainak Mukherjee[2], Nikhil Mall[3]

[1]*Dept. of Electrical Engineering*
University of Petroleum & Energy Studies
Dehradun, India
jaideepleo31@gmail.com

[2] *Dept. of Electrical Engineering*
University of Petroleum & Energy Studies
Dehradun, India
mainakmukherjee31@gmail.com

[3] *Dept. of Electrical Engineering*
University of Petroleum & Energy Studies
Dehradun, India
nmall793@gmail.com

ABSTRACT

Of late, Solar Photovoltaics (PV) revolution has taken the world by storm. Since the last two years, more solar PV capacity has been installed in the world as compared to any other conventional or unconventional technology. However, it appears as if the world is paying heed to half of the story. On examining the solar PV value chain, it is easy to conclude that the modules are greener only during the power generation phase whereas they have a significant impact on the environment during manufacturing and end-of-life treatment, both of which deals with environmentally harmful materials. With large PV installations comes dire responsibility to investigate the tenets of its end-of-life management. India alone has an installed capacity of 30 GW as of July 2019. End-Of-Life (EOL) management will provide solar PV its due status of being 100% sustainable form of energy. As the solar PV industry goes deep-rooted, it is important to imbibe the circular economy approach. It is well established, environmentally and financially, that utmost importance should be given to reuse and refurbishment before opting for recycling due to its energy-intensive approach. However, the issues of sustainable disposal and possible recycling of unfunctional and defective PV modules along with its electronic components cannot be ignored. This is attributable to the major macroeconomic and environmental impacts.

Highlights:

1. There exists an economic and environmental case for the recycling of solar PV modules.

2. Only the European Union has a stringent directive in place that brings solar module manufacturers under the ambit of the Extended Producer Responsibility Framework.

3. Key Considerations for an overarching siting framework for recycling facilities and collection centers in India.

Keywords— Solar PV, Recycling, End-of-Life Management, Circular Economy

INTRODUCTION

Solar Photovoltaics (PV) have become a preferred source of energy generation due to their noiseless, emission-free and maintenance relaxing operation. It is well equipped to meet the growing electricity demand without experiencing a high environmental cost of burning fossil fuels. Thanks to its distributed generation and modular type it has all the potential to strengthen local economies. With time, solar PV modules have shown the ability to adapt to varied climates, system sizes, and regulatory frameworks. These can produce power for decades if properly maintained. However, it is recommended to decommission them after 25 years of outdoor installation. This is attributed to the reduction in their power generation capacity by 20% over the course of the time. (Jordan & Kurtz, 2012)

The implementation of solar PV has increased manifold in recent years. Currently, global solar PV installed capacity is more than 480 GW out of which India accounts for 30 GW capacity. (Bellini, 2019) Take, for instance, the thumb rule of 10 square meters of space required to install 1kWp of a solar PV system. (Jain, 2018) If we work out a back of the envelope calculation on the above data point, it was observed that approx. 300 square kilometers of the land has been taken up by solar installations till now. Put differently, it is approximately equal to double the area of Vadodara city. (K., 2012) Furthermore, if we consider each panel to be 300 Wp then in the coming decades we will have ten crore solar PV panels for disposal or recycling. Globally, it is estimated that there will be around 60 Million Tons (MT) of PV waste by 2050. (Lozanova, 2018) For India, it will be about 1.8 MT by 2050. (Bridge To India, 2017)

Figure 1: Stages to Life Cycle Analysis and Associated Coordinates *(Saraswat J, 2017)*

Figure 1 depicts the various stages in Life Cycle Analysis (LCA) of a solar module. The solar module during its operation phase is the cleanest form of energy provider. Due care must be taken to ensure that it is considered clean during its entire value chain. Hence, this presents a case for solar PV recycling policy, standards, and guidelines to avoid solar panels from becoming a burden on the environment.

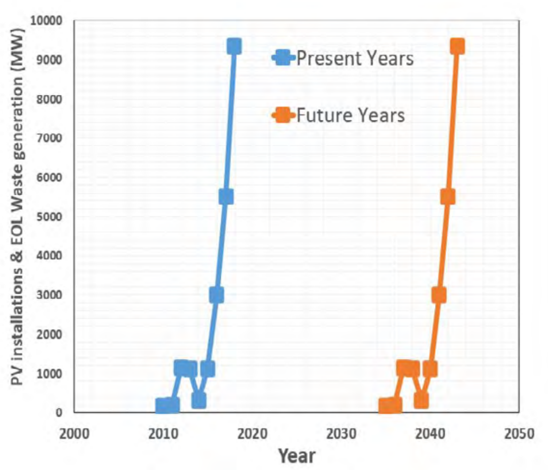

Figure 2: Hockey Stick Curve for Solar PV Installations and End-of-life Waste Generation in India *(Bridge To India, 2017)*

It can be seen from Figure 1 that the solar PV end-of-life waste generation will initiate around 2035 and will become critical around 2040. The graph doesn't provide information on early losses due to natural disasters, site mishaps, poor quality, etc. To handle this gargantuan quantity and to convert this barrier into an opportunity, meticulous planning and ideological clarity is the need of the hour. More importantly, enough emphasis should be there on the recovery of materials from solar modules to ensure the long-term success of the PV industry. (Schoder, 2018)

However, the feasibility of a recycling program depends on sundry elements like - the geographic location, proximity to the recycling facility, the economic value of the material recovered, etc. As the solar PV industry gets deep-rooted, the issues of sustainable disposal and possible recycling of unfunctional and defective PV modules and electronic components become increasingly important. In turn, this has the potential to become a full-fledged industry of its own which will have major macroeconomic impacts like the creation of employment opportunities, an increase in national income, etc. Also, some of the solar PV modules include a minor percentage of hazardous materials like cadmium, lead, etc. which stems from the need for safe disposal or recycling to avoid environmental hazards.

Apparently, the benefits of recycling a solar cell might avoid the hassle of making it a mandatory obligation through policy and guidelines. Firstly, the recycled wafers if used for solar cell manufacturing, leads to an increase in efficiency in comparison to the newly manufactured wafers. This can be credited to the increased purification of the wafer during the second processing cycle. (Fthenakis, 2000) Secondly, the recycling of silicon wafers and solar cells is more environment-friendly as compared to manufacturing new solar cells due to a significant decrease in the consumption of energy and chlorinated chemicals. (Choi & Fthenakis, 2010) (Poseidon Solar , n.d.) Thirdly, recycling can effectively save natural resources from over-exhaustion.

This article provides a review of established solar PV recycling technologies and sketches out the status quo of recovery efforts taken globally in the form of policies and guidelines. Further, this paper provides insight into the current Indian solar PV landscape and underlines key interventions that will provide direction to the policymakers to draft an India specific policy and guidelines.

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ASSESSMENT OF VARIOUS SOLAR PV DISPOSAL METHODS

Solar PV cell converts the incident sunlight into electricity through photovoltaic conversion. Firstly, light shone on the solar cell excites an electron from the valence band to the conduction band. These electrons are then collected by the electrode which assists their flow through the external circuit (Load).

As a single solar cell generates power which is insufficient to power household devices, they are connected in series to form a 'Module'. Further, these modules are connected in series to form an 'Array'.

Several solar PV technologies are available in the market. The classification based on the generation of solar cells is shown in Figure 2.

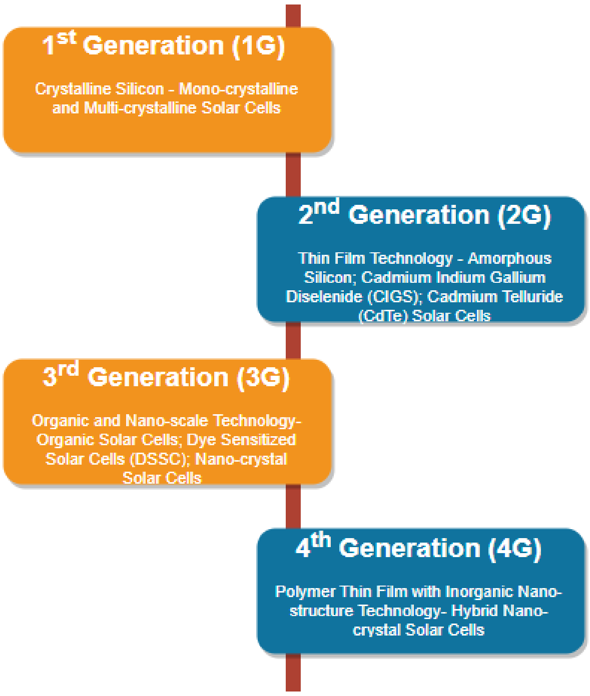

Figure 3: Classification of Solar Cells *(Verma, 2016)*

Although, solar cells have seen various advancements over the years, still, modified 1G crystalline silicon is the most commercialized technology worldwide. Almost 95% of solar PV manufactured in 2017 was crystalline silicon. (Fraunhofer Institute for Solar Energy Systems, 2018) In India, crystalline silicon accounted for 93% of the market share as of December 2018.

A typical crystalline silicon solar PV module comprises of silicon solar cells, metal contacts for electron collection and cell integration, an encapsulation layer, glass panel, back surface field, aluminum frame as shown in Figure 3. There is also a junction box along with cables at the back for further interconnection in the system. Clearly, glass and aluminum frame aggregates to most of the percentage of these modules by weight.

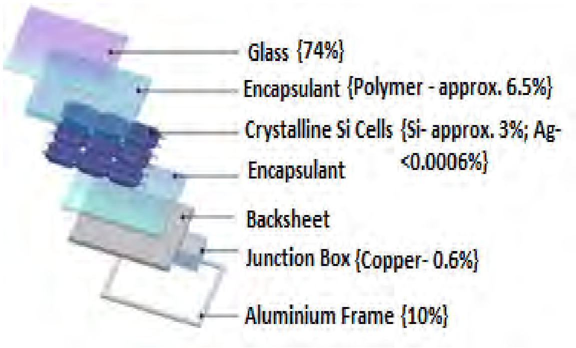

Figure 4: Components of a typical crystalline-Si Solar PV Module by weight *(BINE Informationsdienst , 2010)*

On the other hand, in thin-film modules, the percentage of glass is significantly higher at around 85% and can reach 95% in some of the cases. This is due to a higher optical absorption coefficient as compared to crystalline silicon PV modules. (Shah, et al., 1999) As a result, even a thin film can meet the power generation requirement.

On the circumstance of drilling down, it has been observed that the quantity of silver used has decreased tenfold since 2005 and silicon content has reduced from 7g/Wp in 2005 to 5g/Wp in 2017. (MacMahon, 2018) Also. Although both have a significant amount of glass as raw material, it becomes difficult to have an economically viable recycling process due to the low resale value of the glass. (Berg, 2018) This makes recycling more challenging from a financial perspective. However, recent analyses on decommissioning cost optimization suggest a profit of up to USD 1.58 per module. Globally, by 2030, the value of product recovered from recycling is expected to exceed USD 450 million. There is a big-ticket opportunity to positively influencing the solar project economics by USD 0.01-0.02 /Wp through project decommissioning by deploying high-value recycling scenarios. (Sinha, et al., 2018) Moreover, with economies of scale, improvement in technology, and implementation of incentive mechanisms (Market reforms and Regulatory Framework), the cost of

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recycling will reduce eventually while the cost of the landfill will keep overshooting. (Springer, 2018)

Still, to address the menace of the growing number of old and damaged modules, there are several methods including variants of recycling that are employed across the world:

1. Sending them to landfills after removing the easily detachable materials like aluminum frame, junction boxes, etc.
2. Warehousing these panels until a pragmatic recycling scheme/policy is out.
3. Lastly, sending them to a recycling facility. (Pickerel, 2018) These recycling facilities can be of following types:
   a. **Selective Repair** – Repair of damaged component and reutilizing the module. Although, this can only be implemented if the repair is needed for the junction box or the cables and connectors.
   b. **Major Component Separation-** Extraction of major components like Aluminum, Glass, Junction Boxes, etc. The metal parts are sent to smelters for recycling. The glass fraction, still contaminated with silicon and polymer, is sent to the low-value glass fiber manufacturing industry. The remnants are disposed of at a landfill after being incinerated at a Municipal Waste Incineration facility. With an increase in volume, it can pose a serious threat to the environment due to the corrosive halogen emissions from the polymer. (Agency, 2017)
   c. **Silicon and Rare Elemental Recovery** - These can be termed as complete recycling facilities where efforts are made to recover maximum materials possible.

Though most prevalent, landfilling should not be even considered for out-of-life solar panels as some of them contain hazardous materials like lead and cadmium which can sneak in the environment through leachate or open burning. (McNeill, 2016) However, it can only be avoided completely when it is ensured that the cost of recycling is so low that any other option doesn't seem viable. If recycling is not considered, more than 60 million tons of PV waste, globally, will end up in landfills by 2050. (Saur Energy International, 2018)

Recycling of modules is technically challenging since it contains many adhesives and sealants due to their inherent nature to last out a significant period. Still, several processes have been explored to recycle them. These processes also depend on the usage of the end product. Table 1 and Table 2 enlist the process of recycling solar modules with an aim to manufacture new modules a.k.a primary recycling. It is important to mention here that, still, recycling of heavy metals like lead and cadmium is not yet feasible. (Solar Mango, 2015)

Table 1: Process of Recycling Crystalline Silicon PV Module *(GreenMatch, 2018) (Søndergaard, et al., 2014)*

SR. NO.	RECYCLING PROCESS
1	Disassembly of aluminum frame and junction boxes with cables {100% metal reused}
2	Crushing the rest of the module in Hammer Mill {<5mm}
3	Sorting of Glass and EVA on passing through leach drum and vibrating screen {95% of glass reused}
4	Thermal processing at 500 ̊C to evaporate Ethylene-vinyl Acetate (EVA) coating {reused as a heat source}
5	Etching and melting broken wafers for reuse in new modules {85% of silicon reused}
6	Silver can be extracted on treatment with nitric acid

Other methods to remove EVA include dissolution in organic solvents like trichloroethylene or o-dichlorobenzene. These are capable to dissolve cross-linked EVA at nominal temperature. Also, it can lead to a successful recovery of silicon cell without any damage by avoiding crushing and hammering step. A notable drawback of this method is the cracking of the cell due to the swelling of EVA in the absence of external mechanical pressure. (Doi, et al., 2001)

Table 2: Process of Recycling of Thin-film PV Module

SR. NO.	RECYCLING PROCESS
1	Crushing the module in Hammer Mill after passing it through the shredder {<5mm}
2	Segregating solid and liquid with a rotating screw
3	Removing film using acid and peroxide from solid segregated material
4	Removing interlayer materials with vibration and subsequently rinsing the glass {90% of glass reused}
5	Segregated Liquid goes through precipitation and dewatering for separation of metals {95% semiconductor material reused}

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As per empirical analyses, around 90% of the module's glass and 95% of the semiconductor material can be recovered during this process. This is a case when the sector is at the nascent stage, and the innovative technologies are still being developed.

Solar modules can also be recycled to form different material called tertiary recycling. Studies have shown that the solar cell residue, after removal of aluminum frame and glass, can be used as an admixture to construction material. More specifically, the addition of solar cell residue up to 5% in cement media does not alter the hydration products. (Fernandez, et al., 2011) This will provide benefits like low CO2 based cement, lower cost, etc.

HAZARDOUS ELEMENTS USED IN SOLAR PV MANUFACTURING AND THEIR EFFECTS ON HUMAN HEALTH

Aluminum and glass account for the major portion of the solar PV module. Both are available in large quantities in the earth's crust and do not pose any hazard to the human body. However, the rare elements like gallium, germanium, etc. pose a dual problem- shortage, and ill-effects to human well-being.

Gallium is present in GaAs (Gallium Arsenide) modules, CIGS (Copper Indium Gallium Diselenide) modules, concentrating PV, etc. Germanium is present in amorphous silicon modules, concentrating PV, etc. Cadmium is a part of CdTe (Cadmium Telluride) modules whereas lead is a part of perovskite solar modules. (Zhang, et al., 2018) Silver makes a grid (fingers and busbars) on solar cells for the collection of photo-generated electrons and subsequent transfer in the external circuit. Table 3 enlists the major health effects of these hazardous elements on the human body.

Table 3: Likely Effects of Hazardous Elements on Human Health *(Centers for Disease Control and Prevention, 2018) (Bernanrd, 2008) (M, et al., 2001) (Lenntech, 2018) (White & Shine, 2016) (Drake & Hazelwood, 2005) (Duruibe, et al., 2007)*

ELEMENTS	LIKELY EFFECTS ON HUMAN HEALTH
`	1. Risk of High Blood Pressure 2. Kidney and Heart-related disease 3. Reduced Fertility etc.
Cadmium	1. Risk of Kidney related disease 2. Bone Demineralisation 3. Impair Lung function and can aggravate the risk of Lung Cancer etc.
Selenium	1. Affects Metabolism of Growth Hormone 2. The risk to Endocrine Glands 3. Dermatologic effects like Nails and Hair loss
Gallium	Pure Gallium is not harmful to the Human Body. However, on reaction with other elements like chlorine can cause- 1. Throat Irritation 2. Difficulty in Breathing 3. Chest Pain 4. Partial Paralysis etc.
Indium	1. Indium Lung Disease etc.
Silver	1. Permanent bluish-grey discoloration of the skin (Argyria) 2. Permanent bluish-grey discoloration of eyes (Argyrosis) 3. Kidney and Liver Damage etc.

INTERNATIONAL COMPARISON OF EOL SOLAR PV MODULE DISPOSAL GUIDELINES

In the United States of America (USA), there is still no federal policy for recycling of solar PV modules. It is still governed by various state policies and the Federal Resource Conservation and Recovery Act. (Niclas, 2014) However, for these modules to come under the purview of RCRA require failing the Toxicity Characteristics and Leach Procedure Test (TCLP), which they don't due to the significant leeway given under the guidelines. Hence, in 2017, Washington became the first state to pass a mandate on solar PV recycling by asking manufacturers to submit a plan by January 2021. (Legislature, 2017) However, there is an inherent limitation in the state-level mandates of circumvention, where the waste can be dumped in other states with no regulations. It is important to take note of certain module manufacturers who defied all odds and provided extended producer responsibility for the recycling of solar PV modules. Some of these were First Solar, SunPower, Abound Solar, etc.

In the European Union (EU), the recycling approach for electron waste (e-waste) is being guided by the Waste Electrical and Electronic Equipment (WEEE) Directive. The directive became law in 2003 and made it mandatory for the manufacturers to institute and

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organize infrastructure to collect their e-waste free of charge for private households. They were mandated to recycle or dispose of in an ecological manner. It was in 2014 when solar PV modules became a part of the WEEE directive through an amendment. Since then, the module manufacturers in the EU are liable to think through the recycling strategy of its modules and price them accordingly. There are sundry models developed and implemented in the union on recycling. These include- the cost of recycling being borne by the producers; sharing the cost of recycling with the consumers through mutual agreements or with other producers under a joint-and-several liability framework. Further, the European Standards Organization, in 2017, developed standards for collecting, transporting, reusing or recycling under the directive. It specified the quantity of halogen in the material to be incinerated. These standards are being met today but with the increased influx of modules, it might be difficult to meet these norms.

More importantly, the definition of the word 'manufacturer' was left to the discretion of each member country (28) of the bloc. The need arose when certain groups like installers, importers, re-sellers found a way to by-pass the legislature.

Few international bodies for PV recycling are enlisted below:

1. **PV Cycle**- As an initiative it started in 2005 with an aim to mainstream recycling in the PV sector. Two years down the road, it was established as a PV Cycle Association headquartered in the EU (Belgium), a not for profit organization that provides customized solutions for waste management of solar PV modules. It provides an end to end waste management solution to its member organizations at a cost-effective rate. Since its inception, the association has processed a total of 27,195 tonnes of solar PV waste. Furthermore, the PV cycle has broadened its portfolio to batteries, industrial waste, e-waste, and packaging. (Cycle, 2019)
2. **ReMedia**- It is an Italian consortium, established in 2005, of approximately 2,200 members that are under the purview of the WEEE directive. This consortium deploys recycling schemes for all types of e-waste like telecommunication equipment, computers, laptops, batteries, etc. Through constant adjustments and optimizations, it has established a fool-proof system of guaranteeing end-of-life management of PV modules. (Remedia, 2017)
3. ***Solar Energy Industries Association (SEIA)***- It was established in 1974 as a non-profit trade association for solar in the USA. It has initiated a national program an end-of-life management program for its member organizations. (SEIA, 2018) The association has established a PV Recycling Working Group which provides recycling services to installers, developers, system owners, third parties, etc.

Since the solar PV industry is at a nascent stage the decommissioning rate of out-of-life PV panels is almost negligible. Hence, of late, most PV modules disposed each year comprises of defective and damaged modules. But the day when the need for recycling infrastructure will be felt is not far away. Also, existing defunct modules must not be discarded, as they contain valuable elements that will get scarce and expensive in the future.

In France and most of Europe, the usual trend for recycling solar modules was the removal of aluminum frame and glass at the general-purpose glass recycling facility which was used to manufacture new modules. On the other hand, the material remained was incinerated in cement kilns. Veolia has opened the world's first solar PV recycling plant in France in 2018. This has been done in coordination with the PV cycle and aims to recycle 1300 tonnes of PV modules in 2018. It has an ambitious target to ramp up to 4000 tonnes by 2022. (Clerq, 2018) However, this plant does not support recycling of the thin-film modules as they make only minuscule percentage of France's market. (Veolia, 2018)

In Germany, in 2015, the WEEE directive was incorporated into the national law. However, the manufacturers were proactively maintaining a National Register on waste equipment in response to the directive. This eased them in meeting targets set under the directive. In 2018, a pilot solar PV recycling plant has fared well. It was instituted by, Geltz-Umwelt Technologies, who has incorporated the ELSi system comprising mechanical and electrochemical processes to extract at least 95% of the material. It aids in easily detaching glass by dissolving the undesired polymer layers. Moreover, the facility has deployed a thermal burner and a quenching system to treat the draft from mechanical processes. (Power, 2018)This facility has the potential to cater to 50,000 crystalline silicon modules per year which are about 1,000 tonnes of modules in terms of weight. (Anon., 2018)

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In China, the tenet of Extended Producer Responsibility (EPR) on e-waste treatment has been imposed under thirteenth-5 Year Plan. However, the solar modules are out of the ambit of this framework as they are not classified as e-waste. Recently, China has started the PV Recycling and Safety Disposal Research Program as a part of the National high-tech R&D program to provide direction to this urgent area.

Currently, apart from the EU, many countries do not have a sturdy PV module recycling infrastructure in place. It has put in place an overarching plan for assigning liability, setting recycling targets, stakeholder awareness, etc. that is bearing beneficial results in environment and market context.

CURRENT RECYCLING INFRASTRUCTURE IN INDIA

India has a very lean solar PV manufacturing capacity in comparison to China. India's solar PV manufacturing capacity comprises of 3 GW of solar cells and 9 GW of solar modules, as of 2018. (Indian Solar Manufacturers Association , n.d.) However, this capacity is not enough to meet the ambitious target of 175 GW set by the government of India. (Press Information Bureau, 2015) Since it requires India to install 15-20 GW every year till 2022. This paved the way for flooding of Chinese modules in Indian markets over the last few years. There is an evident lack of coherence on the take-back policy of these Chinese modules in India.

E-Waste Management and Handling Rules were notified in 2012 but remained ineffective due to the absence of a binding framework and set of targets. In 2016, the amendment brought about changes in its ethos by incorporating rules based on EPR and target setting for producers. Target setting is based upon sales volumes and lifespan of the product. However, the targets are set only for the collection and transportation of the waste to the producer and not on the actual quantity recycled. As per the latest estimates from the Central Pollution Control Board (CPCB), only 4% of e-waste is being recycled in the organized sector between 2015-17. Clearly, enforcement of existing regulations is feeble.

Ministry of New and Renewable Energy (MNRE) has released guidelines for grid-connected solar power projects in which the onus of disposal of the PV modules has been given to the developers. The developers are responsible for the collection of out-of-life PV modules from the site and dispose of them as per 'e-Waste (Management and Handling) Rules' notified by the Ministry of Environment, Forest and Climate Change and as revised and amended from time to time. (Ministry of New and Renewable Energy, 2013) (Ministry of New and Renewable Energy, 2016) However, the paradox is that solar modules are not considered e-waste. Furthermore, some solar installations incorporate tracking systems that require actuators, controllers, Light Detection Resistors (LDRs), etc. (Saraswat, et al., 2018) There is a cloud of uncertainty that is perverse on their inclusion in the rules as well.

Currently, there are only a few organizations that are working in the silicon wafer and solar cell recycling domains in India. (Poseidon Solar Services Pvt Ltd, n.d.) (Recycle Solar Technologies Limited , n.d.) Rest is all the unorganized sector indulged in aggregating e-waste like modules and batteries.

As of now, India is grossly underprepared to manage the influx of e-waste that is expected to increase sharply year-on-year. Also, it is urgent to clarify whether India has acknowledged the negative impacts of renewable energy in meeting the targets set under the Paris Agreement. (Kumarankandath, 2016) Solar PV recycling technologies, policies, and guidelines can spur interest in India which will lead to long term environmental and socio-economic benefits.

CASE STUDIES

SunPower Corporation, U.S.A- It is a one-of-its-kind individual organization that has embedded extended producer responsibility at its very core. This came suo moto from the organization when the need for recycling was at an alarming level and there was no regulatory intervention from the state.

It was established in 1985, in the USA, with solar innovation as the fulcrum of its business model. To date, it has more than 750 patents for sundry solar technologies. In 2017, it received Cradle-to-Cradle certification for its E and X series solar modules from Cradle-to-Cradle Products Innovation Institute. (Corporation, 2017) This certification is bestowed on products that are produced with sustainability as the heart of development. It values safe (human and environment) sourcing of raw materials, manufacturing the finished product using green energy sources, incorporating water conservation principles, and ensure proper recycling at the end of the product life.

Poseidon Solar Services Pvt. Ltd., India – It was set up in 2003, in Chennai (Tamil Nadu), with an aim to recycle silicon wafers and solar cells to bring back the dead material back into the value chain. The major benefits that can be accrued are reusing silicon of higher purity as a substitute to polysilicon for cell manufacturing and using a fraction of energy needed

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for manufacturing an equal amount of new silicon wafer. It has the worlds' first fully automated recycling facility for solar PV applications capable of handling 500,000 wafers or 50 MT of broken silicon material per month. It provides services like cradle-to-cradle and cradle-to-grave to several European companies that have to follow stringent recycling norms under the WEEE directive in the most transparent manner possible. There is the 'Track and Trace System' which places RFID tag on the material, the moment it enters the facility, providing all the relevant details like the stage of purification, data logging, etc. on a web portal to the customer. This assures them that the entire material is being recycled to the specification. (Solar, n.d.)

KEY RECOMMENDATIONS

It is important to take specific actions beforehand rather than when we are in the middle of the problem.

Education, Training, and Workshops

1. Reinforce the need for the development of the ecological design of solar PV modules by R&D centers that is durable and recyclable at the same time. Incentives from the Government of India (GOI) will go a long way
2. Identify commercial e-waste recycling companies and provide them concerted training on solar module recycling and its budgeting
3. Launch solar recycling courses in 'Suryamitra' Skill Development Program to train manpower for the reliable recycling process

Policy & Regulations

4. The GOI has taken sundry steps to achieve targets set in the Paris Agreement. (Saraswat, et al., 2017) To sustain intent to mitigate climate change by bringing solar modules under the ambit of E-Waste (Management and Handling) Rules like several other
5. Set targets for manufacturers to recycle solar modules and ensure efficient enforcement

Data Collection and Analyses

6. Track and forecast the solar PV waste to develop a roadmap for smooth roll-out of recycling infrastructural
7. Develop a recyclability index of solar module manufacturers based on parameters like the amount of material that can be recycled, ease of recycling, environmental impact, etc.

Technical Innovation

8. The lifetime of solar cells is much longer than the module assembly. Using thermoplastic as encapsulant instead of EVA can drastically reduce the cell breakage during recycling (CU-PV, 2016)
9. With time, solar PV module designs are evolving rapidly. This poses a unique problem of designing recycling facilities that can accommodate the influx of past, present, and future modules efficiently.

Contracts

10. Encourage developers/ manufacturers to include the cost of decommissioning and recycling of PV panels
11. Explore ways to fund recycling by the escrow fund set aside at the time of construction of the project

Strategy Refresh

12. Decommissioning and transportation to be done by reverse logistics companies or authorized dismantlers. This has been observed to fructify in the past for small and remote installations.
13. Institute an entity/association/consortium of PV module manufacturers dedicated for PV recycling
14. Nudge the manufacturers to think out-of-box in developing strategies that can ease the recycling process
15. Establish a channel of communication between the Indian Solar Manufacturers Association and Waste and Recycling management industry
16. Demonstrate a case for the financial viability of high-value recycling through positively influence on project economics. Energy Payback Time (EPT) can be used as an important criterion to compare amongst the modules with new wafers and the modules with recycled wafers. Several studies have shown that EPT for recycled wafers is less than half of the EPT for new wafers. (Müller, et al., 2006)

WAY FORWARD

Based on the following Figure we are in the process coming up with a tool. The data necessary is available in the public domain but at different locations. Hence, there is a need to patiently collect and sort the data. Once done, we will initiate GIS mapping the results of which we intend to publish in the next phase.

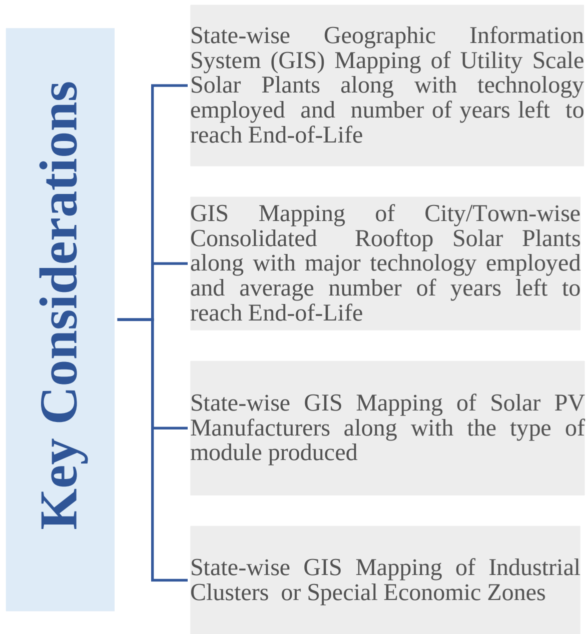

Figure 5: Key Considerations for Siting Framework

Though the analyses will be done for PAN India, it is prudent to take up each state individually. Once the analyses are done state-wise, we will coagulate the information to develop an overarching siting framework for recycling facilities and collection centers after critically examining the need for warehousing prior to recycling. This information gathered will help us in locating the recycling facility as well as its capacity. It will also provide a timeline for setting new recycling facilities based on the availability of throughput. Once the location has been identified, it will make sense to identify the manufacturing industries nearby which demand the recovered material. This will lead to the development of an effective collection program and forecasting framework that is classified as the most cost-intensive intervention.

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