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Alliance for an Energy Efficient Economy

Projecting National Energy Saving Estimate from the Adoption of

Adaptive Thermal Comfort Standards

in 2030

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Alliance for an Energy Efficient Economy (AEEE) is a policy advocacy and energy efficiency market enabler with a not-for-profit motive. Based out of New Delhi, it is the only organisation in India which works on creating awareness about energy efficiency as the 'first' resource. It advocates for data driven and evidence-based energy efficiency policies that will unleash innovation and entrepreneurship within the country to create an energy-efficient economy. AEEE works using a collaborative approach on multiple projects in the following thematic areas that encompass almost all aspects of energy efficiency: ESCO & financing, buildings & appliances, urban infrastructure and smart grid & utilities. AEEE has also partnered with leading organisations to bring a vibrant synergy in the impact of its work.

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Executive Summary

Background

India's cooling energy needs are projected to grow significantly within the next decade, with far reaching environmental and societal impacts. The Government of India (GoI) has elevated addressing India's cooling challenge as a national priority and is actively engaged in developing a National Cooling Action Plan. A recent study by Alliance for an Energy Efficient Economy (AEEE) projects that just within the next decade, India's cooling energy demand will grow 2.2 to 3 times over the current level, under moderate-growth or potential high-growth scenarios respectively. Of this overall nationwide cooling demand, space cooling, i.e. comfort cooling in the building sector, comprises 50% of the total; this sector also shows the maximum improvement potential in terms of energy saving and carbon emission reduction. Space cooling thus represents a key opportunity area for proactively managing India's cooling energy demand.

With most of India's air-conditioner stock yet to come, now is the critical window of opportunity to build in interventions that will have a meaningful impact on the future space cooling related energy consumption and emissions. Given the criticality of what is at stake, all possible levers will have to be pulled to make a collective difference: building energy efficiency, equipment efficiency, alternate cooling technologies, as well as user behavioral adaptations. Adaptive thermal comfort (ATC) has been recognized as a definitive means to achieving energy savings by building scientists and research groups the world over, and offers a low-capital intervention opportunity to achieve savings through user adaptation. This project aims at probing the impact of its nationwide adoption in 2030, specifically estimating what would be the nationwide energy savings potential through widespread adoption of ATC.

Project Scope and Objectives

The project scope includes four components:

1. Theoretical assessment of the energy saving opportunities using adaptive thermal comfort in residential and commercial building
2. Empirical assessment of the HVAC usage pattern in commercial buildings to understand the cooling demand
3. Lab testing of RACs to validate energy saving opportunities under adaptive thermal comfort standard
4. Evaluation of the key policy options for achieving the energy saving potential

The intended outcome of the project is two-fold:

- To project national energy savings estimate from the adoption of adaptive thermal comfort standards in residential and commercial buildings
- Based on the research outcomes and the evaluation of the existing policy framework, recommend policy options and market transformation strategies that would help achieve the energy savings potential from the adoption of ATC

Project Components and Their Findings

- **Literature review:** The project involved an exhaustive review of secondary literature exploring indoor thermal comfort, temperature set-points and ATC related information for both residential and commercial building sectors, specific to the Indian subcontinent. The commercial sector literature (including existing simulation results) points to two findings: firstly, ATC is not a prevalent practice in India; secondly, that for every 1°C increase in set-point, approximately 1% energy savings can be expected. Existing literature did not provide meaningful insights into the residential sector and this was identified as a data gap. To close this data gap, AEEE conducted a national survey on RAC usage propensities in Indian homes, in order to inform this project and also have wider applicability for future works related to space cooling.

- *Commercial Building Survey:* A commercial building survey was carried out to understand the HVAC usage patterns and specifically the temperature set-point preferences. The survey aimed to map trends in air-conditioning usage in large commercial buildings and capture the O&M practices followed by building owners and facility management entities. The survey highlighted the following key points:
  - There is little awareness of the concept of ATC
  - Most prevalent set-points temperatures range between 22°C -24°C;
  - Commercial buildings operators believed that 1°C -2°C increase from the existing set-points should be acceptable to the occupants and will not compromise their thermal comfort levels

- *Residential RAC Survey:* AEEE conducted a nationwide survey to understand the residential RAC usage pattern in India, covering nearly 1000 households in 100+ cities. This survey has generated a first-of-its kind dataset on the RAC utilization in the residential sector which specifically informs the set-point propensities of residential RAC users. The key takeaways relevant to this project are:
  - 24°C is the most preferred temperature in Indian homes. 66% of the population operates RACs at temperatures of 24°C or below, indicating that there is a wide band of population that lends itself to the applicability of adaptive thermal comfort standards.
  - A large share of RAC users (66%) prefer using a fan in conjunction with air-conditioning. This strengthens the case for the applicability of adaptive thermal comfort in the residential sector, since air movement can help widen the ATC temperature range.

- *Establishing acceptable set-point temperatures:* In order to guide the savings estimation, the project explores and establishes acceptable ATC temperature set-points for Indian conditions. For residential buildings this was achieved primarily through literature review (described in section 1.2) and for commercial buildings it was captured through the survey (described in section 3.1).
  - Our exhaustive literature review of studies pertinent to different climatic zones of India suggests that the 'acceptable upper limit' for comfortable temperature set-point, with adequate air movement, for Indian residences falls between 25°C to 27°C depending on the climate zone. For the commercial sector, a combination of literature review and our commercial sector survey suggests an 'acceptable upper limit' of 26°C for comfortable temperature set-point.

- *Air-conditioner Stock Estimation:* The project provides a bottom-up estimation of the current and future (2030) energy needs for air-conditioning of the residential and commercial buildings, for the following technologies: RACs, chillers systems, VRFs.

- *Psychrometric Lab Testing of RACs:* The project scope involved lab testing of RACs to validate energy saving opportunities under adaptive thermal comfort standards. We conducted psychrometric testing of 4 RAC models: a mix of fixed speed and inverter units representing the best-in-class as well as the most prevalent models. The test incorporated 72 test conditions (including standard testing parameters), to evaluate the RACs' energy performance at different outdoor temperatures and indoor set-points. The observed test results, which were discussed with multiple industry experts to help explain possible reasons for the outcomes, were counter-intuitive and showed an increase in instantaneous power draw at higher set-points. This is potentially due to limitations of the test conditions and test setup, which needs to be redesigned to establish energy consumption implications - and not just instantaneous energy efficiency - of indoor setpoint variation. AEEE will be conducting further testing, as an additional project, to reassess these findings, and to home in on empirically validated savings potential through the adoption of adaptive thermal comfort.

- *New Simulations:* While simulation was not part of the project scope, in view of the observed lab-test results, we ran macro-level simulations in order to correlate energy consumption with set-point, and to better inform the energy savings potential from ATC. The simulation findings are aligned with what we found in secondary literature (existing simulations) and suggest:

- ~6% savings per 1°C increase in set-point in RACs
- ~1% savings per 1°C increase in set-point in chiller systems.

- *Estimation of Nationwide Energy Savings Potential from the Adoption of ATC in 2030:* Energy savings were estimated using incorporating inputs from literature review, survey findings, lab testing of RACs, and the new simulations. The key results have been tabulated later in this chapter.
- *Evaluation of the Current Policy Framework and Building Guidelines:* A review of the existing policy framework with respect to adaptive thermal comfort suggest some gaps:
  - The prevalent building codes do not address thermal comfort as such, or incorporate adaptive thermal comfort practices.
  - Existing literature shows little consensus on optimum set points for different building types in different climate zones in India, which leaves room for future work.

Nationwide Energy Savings Potential from the Adoption of ATC in 2030

Key Finding: The overall energy savings potential in RACs, chillers and VRF system in 2030 is tabulated below. **Our analysis shows that the nationwide energy savings potential through the adoption of ATC practices is 8%-13% of the total air-conditioning energy consumption of the building sector. This amounts to savings of 31-54 TWh in 2030.** Relative to the respective energy consumption, RACs show maximum savings potential from ATC, as compared to the savings possible in chillers and VRF systems.

Component	Climatic zone wise national energy savings (TWh)			Total national energy savings (TWh)
	Warm and humid	Composite	Hot and dry	
RACs	11-30	10-16	4-6	27-50
Chiller system	1.1	0.4	0.6	2.1
VRF system	0.7	0.3	0.4	1.3
Packaged DX	0.5	0.2	0.3	0.9
Total	13-32	11-17	5-7	31-54

Future Recommendations

Based on our learnings from the secondary literature and our surveys, and our review of the existing policy framework and the gaps therein with respect to ATC, we see three core strategies that can promote the adoption of ATC and help manifest the nationwide savings potential. Our recommendations grouped within these strategies are as follows:

Core Strategies	Specific Recommendations
Establishing a concept of comfort-temperature range and ensuring its integration in the building codes and design guidelines	• Building codes to establish comfort-temperature ranges which are specific to Indian climate types, as well as building types • Guidelines for HVAC system design should be based on ATC standards
Operational interventions	• Leverage the equipment Standards and Labelling (S&L) program for promotion of ATC, by including information about the comfort-temperatures and their corresponding annual energy use. • O&M guidelines and operating protocols for commercial buildings should emphasise achieving optimum comfort and maximising energy savings from adaptive thermal comfort.
User awareness and messaging to promote the concept of ATC	• Foster user awareness, publicize project successes, and endorse energy savings through ATC as a national agenda.

Endnote: Areas for Further Investigation

There is very limited lab research not just in India but globally on the energy consumption implications of indoor setpoint variation of air conditioners. While our project uncovers some knowledge gaps in this subject, we recommend more extensive research on the co-relation of equipment energy performance and indoor set-point temperatures, including in-situ monitoring of select buildings in different climatic zones and lab tests conducted over longer timeframe. AEEE is conducting detailed lab testing to firmly establish the attainable energy savings through adoption of ATC. Additionally, we did not find any technical literature on how the energy consumption of VRF and Packaged DX systems operating in India would change with a change in temperature set-point. Given the anticipated growth especially in the VRF segment, this should be taken up as a topic for further exploration.

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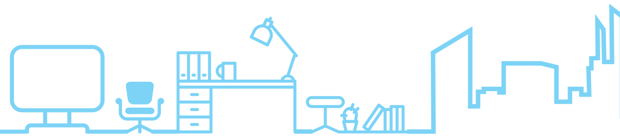

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1 INTRODUCTION

1.1. Background

With an increasing population (> 1.3 billion), rising temperatures (3,120 annual Cooling Degree Days), and an aspirational middleclass, India finds itself in the eye of a perfect 'cooling' storm – all in the milieu of national developmental commitments (Power for All, Housing for All and Smart Cities Mission) and international climate change mitigation targets (Paris Climate Agreement and Kigali Amendment to the Montreal Protocol). Compounding the challenge further is India's rapidly growing built-up area (2-3X by 2030 over 2010)[1] and an extant low penetration of room air-conditioners (5-10%)[2]. A non-trivial increase in the penetration of air-conditioning is predicted in the next decade or so with severe societal and environmental bearings: strain on the electric grid, significant additional power generation capacity, peak load impacts, and an enormous carbon footprint, both direct and indirect. In addition, it creates indefensible social inequity emerging from the asymmetrically distributed impacts of summertime power outages which denies even basic thermal comfort available through fans to those sections of the society that contribute least to peak air-conditioning related demand. This leads to a pertinent question: how does one provide thermal comfort for all in a sustainable and affordable manner, and uphold basic standards of human well-being?

Per a recent study carried out by Alliance for an Energy Efficient Economy, space cooling in buildings (refrigerant and non-refrigerant based comfort cooling) dominates India's total cooling demand (i.e. space cooling in buildings, mobile air-conditioning, refrigeration, cold chain and industrial cooling) and will continue to do so in the next decade or so, with a ~50% share of the deployed cooling capacity, energy consumption and carbon emission. However, the building sector also shows the substantial improvement potential in 10 years' time, at roughly 15-20% saving potential in energy consumption.

These savings can be realised through a combination of interventions of which occupant behaviour is critical. People's perception of thermal comfort depends on their historical exposure to their immediate thermal environment (controlled or uncontrolled) over a long period of time. An extension to this premise is that an average person's perception of thermal comfort will be affected by the average outdoor weather conditions that prevail in and around his/her geographical location. This could have a tremendous impact on comfort conditions in buildings, energy consumption and carbon emission.

1.2. Overview of Existing Literature on Adaptive Thermal Comfort

The set-point temperature within a regularly occupied space/ building represents the thermal comfort requirement of the occupants, where the thermal comfort is dependent on multiple indoor and outdoor parameters. The section discusses the neutral temperature range and set-point range for commercial and residential buildings.

1.2.1 Neutral Temperature for Commercial Buildings

The IMAC[3] study provides a mathematical approach to obtaining the neutral temperature range. It uses a Predictive Mean Value (PMV) model to find the neutral temperature and is relevant for the Indian context compared to the ASHRAE and EN models. The IMAC model provides the neutral temperature for commercial buildings in naturally ventilated (NV), air conditioned (AC) and mixed mode (MM) mode. Since the IMAC model is based on 30 day outdoor running mean air temperature, the climate conditions are also being accounted in the study in parallel to the adaptive comfort consideration of the occupant. The temperature ranges deduced from the study are significantly higher than those suggested by the ASHRAE and EN models, suggesting substantial energy savings in commercial buildings with different ventilation modes. The neutral temperature range suggested by the IMAC is delineated in Table 1.

Table 1: Neutral temperature range for IMAC model

Sr. No.	Type of ventilation in building (NV/AC/MM)	Neutral temperature range
1	Natural ventilation (NV)	19.6°C – 28.5˚C
2	Mixed mode (MM)	21.5°C – 28.7˚C
3	Air conditioned (AC)	23.5°C – 25.5˚C

A study[4] based on lab experimentation of MM commercial buildings suggest thermal comfort range of 28°C - 28.5˚C at Torrent Research Center, Ahmedabad and 24 ± 1 ˚C at Transport Corporation of India (TCI) office, Gurgaon. Another study[5] capturing the mean comfort temperature with the help of lab experiment for NV and AC office spaces in warm and humid climate of Hyderabad and Chennai informed mean comfort temperature as 28˚C for NV buildings and 26.4˚C for AC buildings. Another similar lab experiment[6] in Hyderabad and Chennai for AC buildings indicated thermal comfort temperature range between 26.1˚C - 28.1˚C; whereas, temperature suggested by IBC and ASHRA 55 are in range of 21˚C - 26˚C.

Review of cases analysing international buildings/ cities having similar climatic conditions inferred thermal comfort range as discussed. A lab study[7] conducted for AC offices in Japan suggests the set-point to be at 28˚C. The study further takes into consideration the Kyoto Protocol Agreement in order to reduce the CO2 emissions. Another experiment[8] conducted for the sub-tropical climatic region of China in MM office building, indicated the comfort temperature range as 22.6°C - 29.9˚C, obtained from a derivation of linear regression model. A lab study[9] of commercial and residential buildings found the thermal comfort range as 27.9˚C for NV buildings, 27.3˚C for AC buildings, 26˚C for office buildings specifically. The neutral temperature obtained from the linear regression analysis was 27.7˚C.

A study[10] in tropical and humid environment of Thailand, the comfort temperature range for NV and AC office buildings were analysed as 27.4˚C and 24.7˚C respectively. Study[11] conducted in sub-tropical region of Japan, suggests the occupant thermal comfort temperature to be as 27.2˚C for MM office buildings. Another study[12] in tropical climate of Brazil, for MM office buildings, the set-point of the system was found out to be 22°C - 24˚C in winter and 23°C - 26˚C in summer and the system used for experimental study was kept at set-point range of 21°C - 26˚C. A simulation based approach[13] for AC office buildings in different climate zones of the USA, viz., Miami (hot and humid), San Francisco (coastal mild), thermal set-point was found out to be 24˚C during summer and 21˚C during winter. Another lab experiment[14] based study for AC offices the thermal set-point was analysed for seven different climatic zones in USA (Miami, Phoenix, Fresno, San Francisco, Baltimore, Chicago, and Duluth), the set-point analysed was 25˚C for summer and 20˚C for winter.

Summary table indicating neutral temperature range for different types of ventilation in commercial buildings as obtained from studies undertaken by various researchers is as shown in Table 2.

Table 2: Summary table for Commercial building neutral temperature for different ventilation types.

Sr. No.	Ventilation type (NV/MM/AC)	Neutral temp. range	Location	Climate type
1	AC	26.1°C – 28.1˚C	Hyderabad, Chennai, (India)	Warm and humid
2	AC	28˚C	Kyoto, Japan	Composite
3	AC	21°C – 24˚C	Miami, San Francisco, Mew York, USA	Hot and Humid, Coastal mild, Cool summer and cold winter
4	AC	20°C – 25˚C	Miami, Phoenix, Fresno, San Francisco, Baltimore, Chicago, and Duluth , USA	Seven climate zones as per ASHRAE
5	MM	24°C – 28.5˚C	India (Ahmedabad, Gurgaon)	Hot and dry, Warm and humid
6	MM	22.6°C – 29.9˚C	China	Sub-tropical
7	MM	27.2˚C	Japan	Sub-tropical
8	MM	22°C – 26˚C	Brazil	Tropical

Sr. No.	Ventilation type (NV/MM/AC)	Neutral temp. range	Location	Climate type
9	NV/AC	26.4°C – 28˚C	Hyderabad, India	Warm and humid
10	NV/AC	26°C – 27.9˚C	China	Humid, Sub-tropical
11	NV/AC	24.7°C – 27.4˚C	Thailand	Tropical and humid
12	NV/MM/AC	19.6°C – 28.7˚C	India	Hot and Dry, Moderate, Warm and humid, Composite, Cold

1.3. Neutral Temperature for Residential Buildings

Lab experimentation[15] for NV residential buildings in warm and humid climate of Bangalore, India inferred different thermal comfort temperature range for various seasons, i.e., 20°C – 23.33˚C for winter and 22.22°C – 26.66˚C for summer. Another lab experiment[16] in warm and humid climate of India – Chennai, analysing NV residential building indicated thermal comfort band is in the range of 27.6°C – 30.5°C and the acceptable band in the range of 26°C – 31.8˚C. The study highlighted that the subject under test prefers a neutral temperature of 27˚C.

The study[17] of NV residences of Hyderabad, India indicated comfort range as 26°C – 32.45˚C with neutral temperature as 29.23˚C; whereas, for the same city ASHRAE recommended 23°C – 26˚C for summer and 21°C – 23˚C for winter. Another extensive study[18] conducted in three different Indian cities representing three different climate zones i.e. hot and dry (Ahmedabad), warm and humid (Chennai) and composite (Hyderabad)suggested comfort temperature range as delineated in Table 3.

Table 3: Neutral temperatures for 3 different climate zones in India by Dhaka et. al[16]

Sr. No.	Name of city studied	Relevant climate zone	Neutral temperature range
1	Ahmedabad	Hot and dry	23.7°C – 28.0˚C
2	Chennai	Warm and humid	25.2°C – 27.5˚C
3	Hyderabad	Composite	24.3°C – 27.8˚C

The thermal comfort range suggested for warm and humid climate of Kerala by a study[19] surveying NV residential buildings indicated temperature range as 23.5°C – 28˚C for winter, 28°C – 32˚C for summer and 25°C – 29˚C for monsoon. A lab based experimental study[20] in Jaipur, India, analysed NV and AC residential buildings, the indicated comfortable temperature in the range of 29°C – 34˚C and 23°C – 29˚C for NV and AC buildings respectively. A study[21] conducted in NV hostel (residential) building of composite climate highlights neutral temperature as 30.15˚C and the comfortable temperature as 30.4˚C, 30.1˚C, and 29.8˚C for single, double and triple occupancy rooms respectively.

A laboratory-based experiment[22] carried for NV building at Kharagpur, India suggested neutral temperature as 26.5˚C. The thermal comfort temperature was found to be in the range of 20.9°C – 32˚C. Another study[23] analysing cold climate of India indicated thermal comfort temperature range of 18.6°C – 22.3˚C for winter and 24.1°C – 28.4˚C for summer. Another study[24] of the city of Chennai, India explained temperature humidity index (THI), which is found out to be in range of 21°C – 24˚C.

Lab experiment[25] conducted in the warm and humid region of Cuba, indicated thermal comfort temperature in the range of 26.8°C – 28.2˚C where the standard suggested comfort temperature at 24.4˚C for AC and 22.8˚C for NV buildings. In a laboratory based experiment[26] conducted in suggested the thermal comfort temperatures to be in the range of 23°C – 28˚C and the relative humidity (RH) to be in the range of 50 – 85%.

Table 4 summarizes the neutral temperatures found out from various studies conducted by different researchers in residential buildings. As evident in the table, there is little consensus on optimum comfort range for a particular climate zones, which leaves room for future work in terms of establishing comfort-temperature ranges.

Table 4: Summary table of neutral temperature for residential building for different ventilation types

Sr. No.	Ventilation type (NV/MM/AC)	Neutral temp. range	Location	Climate type
1	NV	20°C – 26.66°C	Bangalore, India	Warm and humid
2	NV	26°C – 31.8°C	Chennai, India	Warm and humid
3	NV	26°C – 32.5°C	Hyderabad, India	Warm and humid
4	AC	23.7°C – 28°C	Ahmedabad, Chennai, Hyderabad (India)	Hot and dry, Warm and humid, Composite
5	NV	25°C – 32°C	Kerala, India	Warm and humid
6	NV/AC	23°C – 34°C	Jaipur, India	Hot and dry
7	NV	29.8°C – 30.4°C	Jaipur, India	Hot and dry
8	NV	20.9°C – 32°C	Kharagpur, India	Warm and humid
9	NV	18.6°C – 28.4°C	Himachal Pradesh, India	Cold
10	Not specified	21°C – 24°C	Chennai, India	Warm and Humid
11	NV/AC	22.8°C – 28.2°C	Cuba	Warm and humid
12	MM	23°C – 28°C	Taiwan	Sub-tropical

2 APPROACH AND METHODOLOGY

2.1. Project Objective

With the projected exponential growth in the Indian AC market, there is a lot of speculation on the GHG and load impacts, and the possible mitigation strategies. However, wide variation in some of the key assumptions and parameters being used to estimate these numbers may cause uncertainty for policy makers. Additionally, there are unknowns such as, how might the national demand for cooling energy be impacted using specific space cooling strategies. This project strives to uncover the impact of one such strategy: adaptive thermal comfort. Through a deep-dive research, under the guidance of LBNL, and in collaboration with CEPT University, the primary objective of this project is to:

- Evaluate the impact of adaptive thermal comfort on air-conditioning usage and on the resulting energy savings potential nationwide in 2030.

2.2. Framing the Project Scope

The project scope includes four components:

- Theoretical assessment of the energy saving opportunities using adaptive thermal comfort in residential and commercial building
- Empirical assessment of the HVAC usage pattern in commercial buildings to understand the cooling demand
- Lab testing of RACs to validate energy saving opportunities under adaptive thermal comfort standard
- Evaluation of the key policy options for achieving the energy saving potential

The intended outcome of the project is two-fold:

- To project national energy savings, estimate from the adoption of adaptive thermal comfort standards in residential and commercial buildings
- Based on the research outcomes and the evaluation of the existing policy framework, recommend policy options and market transformation strategies that would help achieve the energy savings potential from the adoption of ATC

2.3. Overarching Methodology

As a first step, an exhaustive literature review was carried out to: assess the existing ATC practices, to gather reported energy savings from set-point increases and related parameters in residential and commercial buildings, and to gather insights into the acceptable ATC temperature range specific to Indian conditions. While usable information on commercial buildings was more readily available, few meaningful insights could be gleaned on residential room air conditioner (RAC) related user propensities, and this was identified as key a data gap.

The information obtained through secondary literature was complemented using two extensive surveys: The Commercial survey as part of the project scope, and the Residential survey in order to close a data gap and help inform important aspects of this project as well as other space cooling related studies. The primary intent of the surveys was to get a view into the existing set-point preferences, as well as possible acceptable ATC range, in commercial and residential buildings and inform the baseline of energy consumption.

The 2017 (current) air-conditioning equipment stock was estimated using a bottom-up approach using sales data, available stock information, such as published peer-group reports, BEE's S&L database where applicable, and equipment replacement rate. A top-down validation was carried out to calibrate the stock numbers. This current stock information was used to project the 2030 stock using sales projections from market intelligence reports - which factor in population growth, urbanization, real-estate growth, GDP growth, and market trends - and planned efficiency of technologies and foreseeable industry trends over the next decade, as gathered from lab experts.

Per National Building Code (2005), India is divided into five climate zones i.e. hot and dry, warm and humid, composite, temperate and cold (Figure 1). The temperature and relative humidity (RH) characteristics of these five climates are captured in Table 5. As this study is cooling-centric, the climate types considered were limited to hot and dry, warm and humid and composite, as listed in Table 6. The total air-conditioning stock was distributed climate-wise using the following pieces of information: (1) the state-wise domestic and commercial electricity consumption reported by the Central Electricity Authority; and (2) the distribution of RAC stock into residential and commercial use in the ratio of 70:30 in 2030, per BEE.

Figure 1: Climate zone map of India. Source: Bureau of Indian Standards 2005.

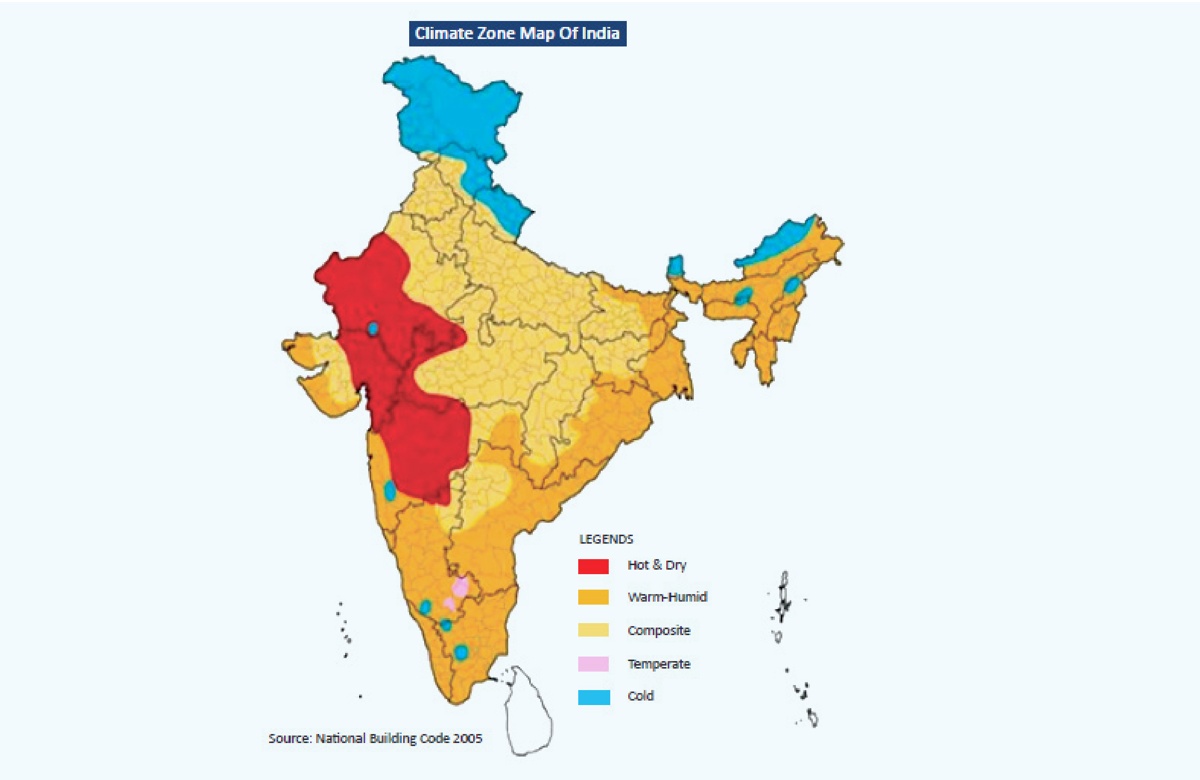


Table 5: Temperature and RH characteristics of India's climate types

Climate type	Summer time temperature	Winter time temperature	RH
Warm and humid	25°C –35ºC	20°C –30ºC.	70-90%
Composite	27°C -43ºC	4°C -25ºC	20-25% (Dry) 55-95% (Wet)
Hot and dry	20°C -45ºC	0°C -25ºC	55%
Temperate	17°C -34ºC	16°C -33ºC	<75%
Cold	17°C –30ºC	-3ºC to 8ºC	70-80%

Table 6: Distribution of Indian States by climate

Climate type	State (or UT)
Warm and humid	Andhra Pradesh, Telangana, Assam, Goa, Karnataka, Kerala, Manipur, Meghalaya, Mizoram, Nagaland, Orissa, Tamil Nadu, Tripura, West Bengal
Composite	Bihar, Chhattisgarh, Haryana, Jharkhand, Madhya Pradesh, Punjab, Uttar Pradesh, Chandigarh, Delhi
Hot and dry	Gujarat, Maharashtra, Rajasthan

A psychrometric lab testing of RACs were run to measure the energy performance as a function of set-point and outdoor temperature. 4 RAC models were tested, incorporating 72 test conditions, to evaluate their energy performance at different outdoor temperatures and set-points. The observed test results were counter-intuitive, showing an increase in power draw with at higher set-points, and could not form a solid foundation for estimating nationwide energy savings from ATC adoption. Hence, the team performed a macro-level simulation to supplement the lab tests to arrive at an alternate basis for projecting nationwide energy savings. AEEE is committed to conducting further testing, as an additional project, to reassess/confirm these findings.

Inputs from all of the preceding steps - i.e. literature review, surveys, air-conditioning equipment stock estimation, lab tests and new simulations - were incorporated towards the estimation of nationwide energy savings potential in 2030 through the adoption of ATC standards.

A final component of the project involved evaluating the current policy framework and building guidelines to gauge the place of ATC as an acknowledged strategy for reducing energy consumption in buildings – emphasis was put on government building codes and other building guidelines. The project proposes a set of future recommendations that address existing policy gaps and are designed mainly with the view of promoting a greater adoption of ATC standards in air-conditioned buildings.

End Note

Given that the lab test results were inconclusive to comprehensively establish the energy savings impact of adaptive thermal comfort, additional research is required to supplement and validate our assumptions.

3 AN INVESTIGATION INTO AC USE PROPENSITIES

3.1. Commercial AC survey

3.1.1 Aim of the Survey

The survey aimed to map trends in air-conditioning usage in large commercial buildings i.e. hospitals, hotels, offices, educational institutions and retail spaces across different Indian climate types. The survey captures the O&M practices followed by leading Facility Managers (FMs) that offer their services in such buildings. The survey was designed to help develop and identify the baseline scenario of energy consumption of air conditioning in Indian Commercial buildings by identifying the employed set-point temperatures in these buildings.

3.1.2 Overview of the Questionnaire

The questionnaire comprised 16 questions classified under four sections viz generic information on HVAC systems, set-point preferences and the occupants' acceptability to higher temperature set-points, occupant thermal comfort satisfaction and cooling energy saving measures. The survey questions along with their underlying intent are included in the Appendix 1.

3.1.3 Administering the Survey

One-to-one personal and telephonic interviews were conducted to obtain FMs' responses to the survey questions. Although, the survey intended to capture all types of commercial buildings, majority of the responses obtained pertained to office spaces and hospitals. Despite our best efforts to reach out to the hotel sector, we did not receive adequate responses.

3.1.4 Key Inferences

- Commercial buildings are broadly classified into fully air conditioned and Mixed mode buildings. In Fully air-conditioned buildings, HVAC systems consume 30-75 % of the total building energy consumption while in mixed mode buildings, HVAC account for 15-35% of total energy consumption.
- The typical EPI (Energy Performance Index) for commercial office space and hospitals ranges hovers around 70-210 kWh/m^2/year and 157-220 kWh/m^2/year, respectively.
- Most buildings use water-cooled central air conditioning systems. Unitary systems are the next most widely adopted air-conditioning systems.
- Most of the buildings are equipped with a Building Management System (BMS) for better control and monitoring of the spaces.
- All the commercial office spaces typically operate on a 24-hour cycle or a 12-hour cycle and use set-points between 22°C - 24°C.

- It was emphasized that occupant comfort is of highest priority in office spaces. However, all FMs believed that 1-2°C increase from the existing set-points should be acceptable to the occupants and will not compromise their thermal comfort levels.
- In hospitals, the responses indicated that irrespective of hospital zones, a 1°C increase from existing set-point temperature is feasible, but this should err on the side of caution in OTs, ICUs and ITUs.
- According to NBC, increased set-point temperatures can be compensated with increased air movement to maintain similar thermal comfort conditions. However, this is highly discouraged in IT office spaces owing to draft induced discomforts and safety concerns.
- Majority of O&M companies have adopted several energy conserving strategies that range from simple automatic door closers systems to sophisticated SCADA (Supervisory Control and Data Acquisition) systems. Few measures include:
  - High performance windows to cut down solar insolation
  - High speed curtains to minimise the infiltration/exfiltration losses
  - Switching to LED from CFL to minimise the sensible load
  - VFD installation, installation of Electronically Commutated (EC) fans and Chiller optimisation for better energy efficiency
  - Hybrid Cooling to improve IAQ and reduce the cooling energy consumption
- And majority of the buildings are adhering to the Energy Conservation Building Code (ECBC) guidelines.

3.2. Residential AC Survey

3.2.1 Aim of the Survey

The premise of energy savings from the adoption of adaptive thermal comfort standards is deep-rooted in the knowledge of room air conditioner (RAC) usage patterns, particularly the set-point temperatures. However, a careful scanning of relevant literature did not provide any meaningful insights into the most preferred (or most commonly used) set-point temperatures in Indian residences. While there is some information available on commercial spaces, mostly in the form of guiding principles that govern the set-points used, the set-points used in homes are largely dependent on human preference which has not been logged in the literature reviewed by the team. To bridge this data-gap, AEEE decided to step beyond secondary research and design/implement a survey that not only informs the ATC project but also gathers a broadly relevant dataset, a first-of-its-kind, on AC usage patterns in Indian residences. This formed the genesis of the survey, 'Mapping the Use of Air Conditioners (ACs) in Indian Households'. In designing the survey, we balanced the need to keep it quick-paced so that it fits within the ATC project timeline, and to make it comprehensive so that we generate meaningful data that has broad-reaching applicability and relevance for further research and projects related to thermal comfort in residences.

3.2.2 Administering the Survey

The questionnaire was short, anonymous, easy to fill out, and comprised 13 questions covering geographical location, house & household size, RAC number, type & runtime, set-point preference, and fan use. The survey was constructed on Google Forms and administered online by popularising it on LinkedIn, Facebook, Twitter, WhatsApp and email. Although a fairly large number of varied responses were collected by deploying this strategy, the team felt that the survey was getting limited to an internet-savvy respondent pool, thus introducing a self-selection bias. Hence, the survey was then physically administered with the help of student-surveyors in the cities of Hyderabad, Chennai, Kolkata, Faridabad, Ahmedabad and Jaipur – these surveys particularly focused on the catchment area of low to mid-income classes (without strictly sticking to definition of these classes).

The survey saw a well-rounded response of 975 households from 100+ towns and cities in States (and UTs); the responses were almost equally divided between the climate zones i.e. hot and dry, warm and humid and composite – of these, approximately two-thirds were collected online while the rest were from physical surveys.

3.2.3 Key Outcomes and Inferences

- The survey average of the number of RACs used per household was 1.7 – this can be corroborated by market intelligence that those households which have already installed one air conditioning unit are more likely to purchase additional cooling systems than households that do not have any cooling products[27]. National Sample Survey Office (NSSO) (2001) reports 1.2 RACs/household; market intelligence supports an increase in the number of RACs/household[28], however, a ~40% increase in less than 20 years can be viewed as aggressive. A linear and predictable correlation between house & household size and number of RACs was observed.
- 1.5 TR of split configuration and BEE 3-star rating is the most popular consumer choice. The existing residential RAC stock of India is new in terms of age of the equipment, with nearly half of the stock being less than three years old.
- Our survey shows that RAC usage is predominantly limited to summer months. 24°C is the most commonly preferred ser-point temperature nationwide. 66% of the population operates RACs at temperatures of 24°C or below. Figure 2 presents additional information on set-point distribution.
- RAC operational preferences by climate zone are summarized in Table 7.

Figure 2: Nation-wide set-point preferences

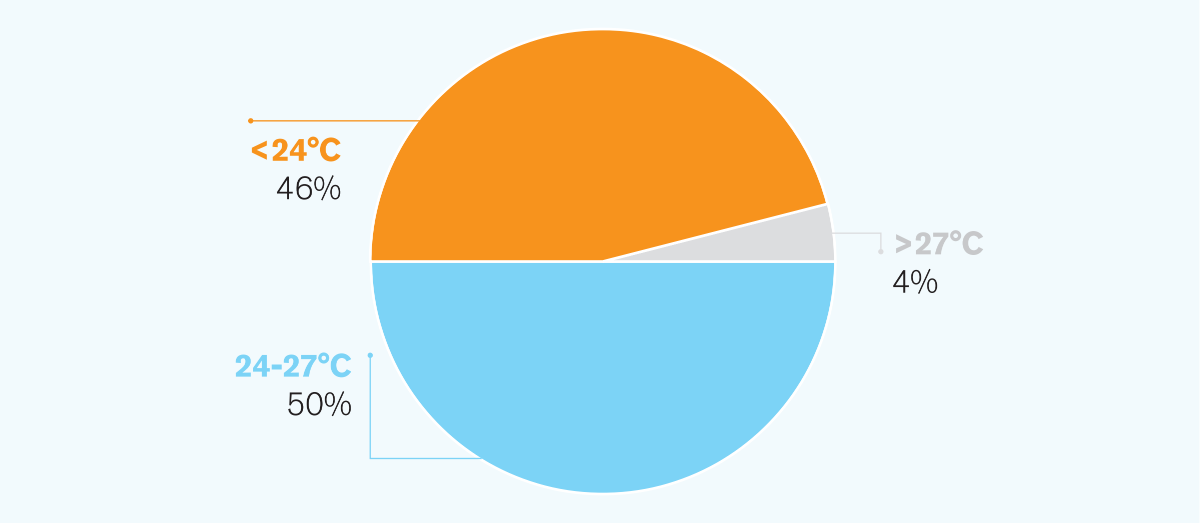


Table 7: RAC operational preferences by climate zone

	Warm and humid	Composite	Hot and dry
Most preferred set-point per climate zone	24°C (27%)	22°C (20%)	24°C (19%)
Annual runtime (hour)	1421	1635	1355
Concurrent fan use	59%	77%	65%

- It was observed that a significant proportion of people (66%) prefer using a fan in conjunction with air-conditioning. This strengthens the case for the applicability of adaptive thermal comfort in the residential sector, since air movement can help widen the ATC temperature range[29]: fans are very pervasive in Indian homes and can almost be thought of as a sociocultural element that all houses are fitted with ceiling fans as default.

4 RAC: PSYCHROMETRIC LAB TESTS

4.1. Lab Testing of Room Air Conditioners (RACs) to Validate Energy Savings Opportunities under Adaptive Thermal Comfort Standard

Psychrometric lab testing of Residential Air Conditioners (RACs) were conducted to evaluate the energy performance of leading efficient RACs available in India in terms of their cooling capacity and energy Efficiency Ratio (EER) for a combination of different indoor set-points and outdoor temperatures. The design of lab tests, results, and inferences are explained in the subsequent sections.

4.1.1 Lab Test Design

The lab testing aims to test the actual performance of a representative sample of RACs in India. BEE's database that documents star-rated RAC production data and the AEEE residential RAC survey (Section 3.2) both point to the dominance of split air conditioners over window air conditioners, and 1.5 TR as the most-prevalent RAC tonnage most bought by consumers in the Indian market. A market intelligence report from BSRIA (BSRIA - World Air Conditioning 2016) points to the significant use of both fixed speed and inverter technologies in India. Hence, we have selected 1.5 ton split type RACs as the sample set for lab testing, including both fixed speed and inverter units. For each type, two different BEE star rated units were selected - high energy performance (5-star rated) and moderate energy performance (3-star rated) - representing a mix of best-in-class as well as the most prevalent models in the market. Table 8 provides the details of RAC units tested under the project.

Table 8: Details of RAC units tested

Unit	Category	Brand	Capacity	Star Rating	Energy Performance
1	Fixed speed	Daikin	1.5 Ton	BEE Rated 5-star	3.65- EER
2	Fixed speed	Voltas		BEE Rated 3-star	3.16- EER
3	Inverter	Daikin		BEE Rated 5-star	5.20- ISEER
4	Inverter	Voltas		BEE Rated 3-star	3.65- ISEER

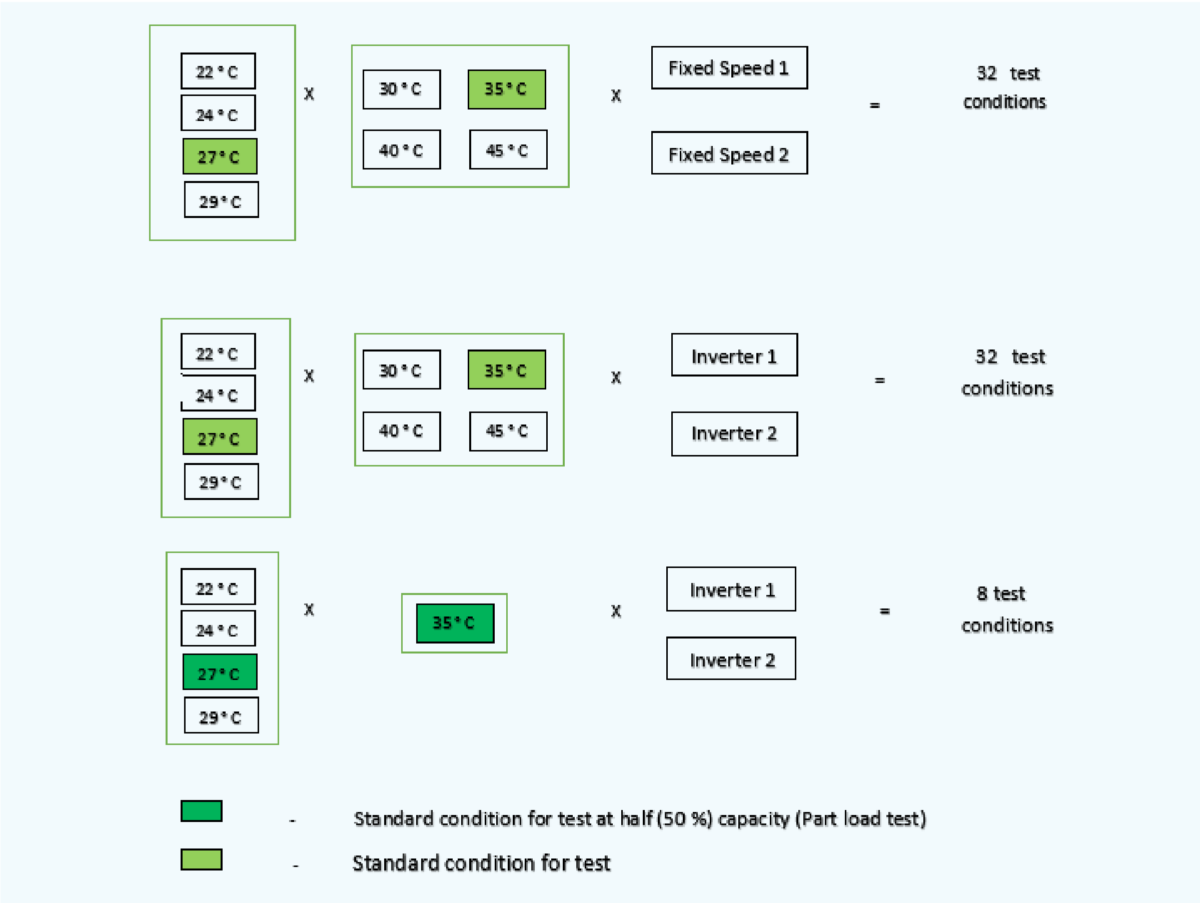
The performance testing of the selected air conditioners was carried out in accordance with IS 1391-2. Performance parameters with respect to the cooling capacity and Energy Efficiency Ratio (EER) were evaluated at four indoor set-points (22°C, 24°C, 27°C, 29°C) and four outdoor conditions (30°C, 35°C, 40°C, 45°C). The selection of the indoor set-points was based on the following rationale:

- 27 °C is the indoor temperature for the standard testing condition for BEE star labeling and hence we included that;
- We wanted pick a set-point above that in order explore stretching the envelope for ATC standards, hence 29°C was chosen;

- Selection of the indoor set-points below 27 °C was informed by the AEEE Residential Survey. Per the survey, 24°C is the most preferred temperature set-point nationwide, and 22 °C is the next fairly common temperature setting. A sizeable population (36%) uses RACs at 22 °C and 24 °C. Hence, these two temperatures rounded up the indoor set-point range used for the lab test.

The design conditions included the performance at standard rating conditions (Indoor - 27 °C, Outdoor - 35°C). Further, tests were carried out to assess the performance of inverter RACs for their part load (50%) efficiency at rated conditions of 35°C outdoor and 27°C indoor. A total of seventy two experimental tests for various controlled conditions were performed as summarized in Figure 3.

Figure 3: Summary of test conditions



4.1.2 Test Methodology

The testing of the air conditioning units was carried out at a Psychrometric (Enthalpy Calorimeter) testing facility. The facility comprised of two adjacent compartments, to simulate the indoor and outdoor conditions for the RACs. The accuracy of cooling capacity measurements was ± 5 %.

Figure 4 shows the schematic of the Psychrometric test facility that is employed for the experiments. The indoor and outdoor compartments in the facility are served by individual air handling units (AHUs). A pressure equalizing device installed between the compartments equalizes the pressure in both compartments. Figure 3 shows a photo of the Psychrometric (Enthalpy Calorimeter) Chamber. Further details of the test chamber are included in Appendix-3.

Figure 4: Test arrangement for RACs inside psychrometric chamber

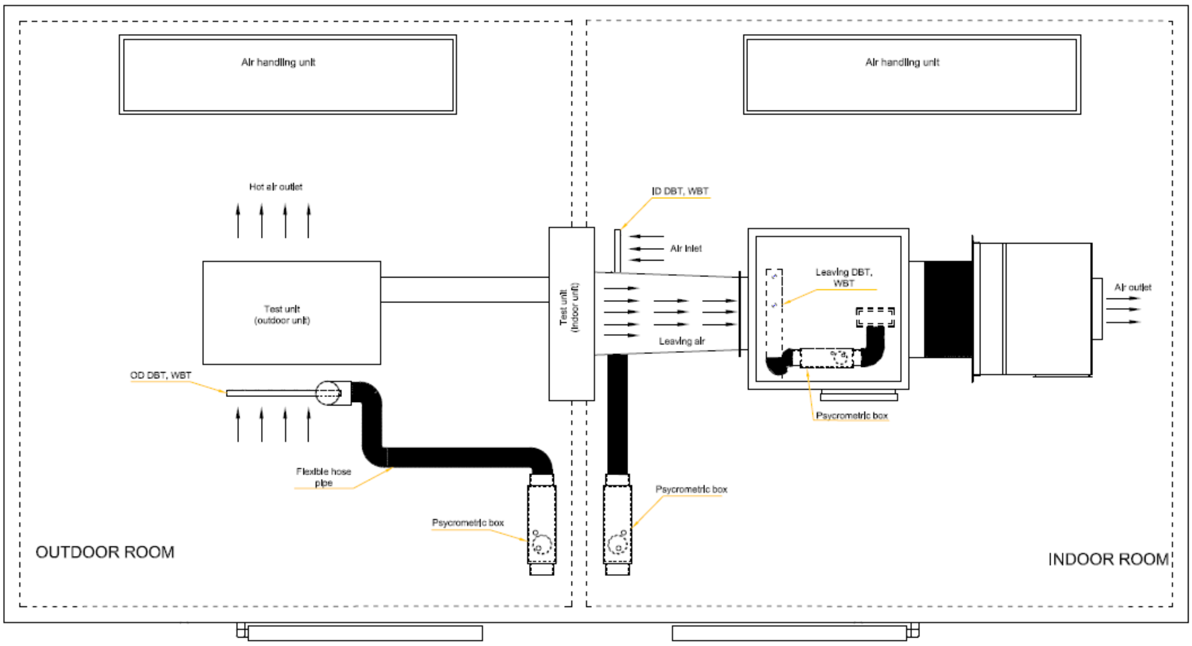


Figure 5: Psychrometric (Enthalpy Calorimeter) Chamber

Experiments were carried out at steady state conditions for a duration of thirty minutes and data was logged for every five minutes to ensure consistency. Additional information pertaining to the accuracy of the measurement devices and the formulae for calculation can be found in Appendix 3.

The following parameters were measured and subsequently derived from the experimental set up:

Table 9: Measured and derived parameters from the lab testing set-up

Measured Parameter	Derived Parameters

• Indoor Dry bulb temperature (Set-point Condition) (°C)
• Indoor Wet bulb temperature (Set-point Condition) (°C)
• Outdoor Dry bulb temperature (Set-point Condition) (°C)
• Outdoor Wet bulb temperature (Set-point Condition) (°C)
• Barometric Pressure (Room) (p_o) (Pa)
• Indoor unit - Outlet Dry bulb temperature (leaving) (°C)
• Indoor unit - Outlet Dry bulb temperature (leaving) (°C)
• Nozzle Differential pressure (h_p) (Pa)
• Nozzle Inlet pressure (V'_n) (Pa)
• Power input (P_E)
    ○ Voltage (Volts)
    ○ Current (Amperes)
    ○ Power Factor
▪ Frequency (Hz)
	• Input air enthalpy (h_{in}) (kJ/kg)
	• Output air enthalpy (h_{out}) (kJ/kg)
	• Relative humidity – Indoor (Input side) (%RH_{in})
	• Specific volume of output air (m³/kg)
	• Volumetric flow rate of air (m³/s)
	• Sensible cooling capacity (Watt)
	• Latent cooling capacity (Watt)
	• Dehumidification capacity (l/hr)
	▪ Energy efficiency ratio (EER)

4.1.3 Results & Observations

This section presents the experimental results in terms of cooling capacity, EER, and input power and the effect on sensible and latent loads for varying indoor (22°C, 24°C, 27°C and 29°C) and outdoor (30°C, 35°C, 40°C and 45°C) air temperatures. In the Figures 4 to 7, all plots on the left represent- cooling capacity vs indoor set-point variation on primary axis and power input vs indoor set-point variation on secondary axis; all plots, on the right represent: EER vs indoor set-point variation on primary axis and power input vs indoor set-point variation on secondary axis. Figures 6 and 7, capture the Inverter RACs performance and include additional performance curves of part load capacity (50%).

Figure 6: Cooling Capacity & Power Input over varying indoor temperature (Left) and EER & Power Input over varying indoor temperature (Right) at 35°C outdoor for Daikin fix speed AC

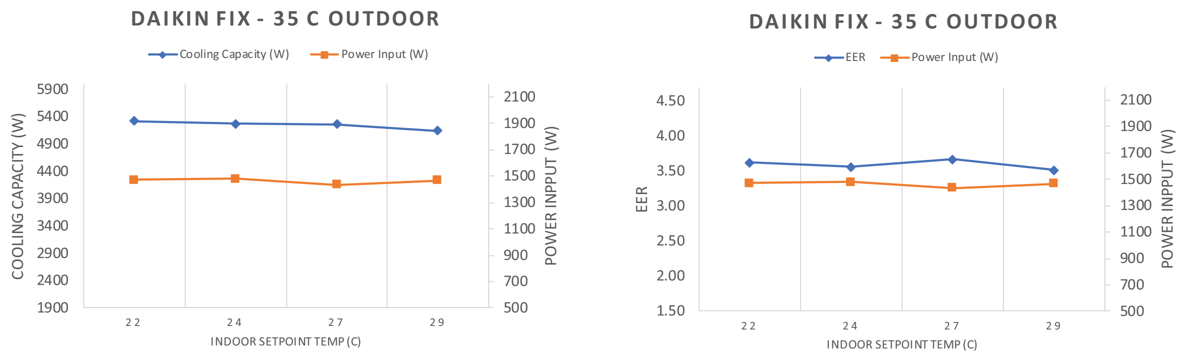


Figure 7: Cooling Capacity & Power Input over varying indoor temperature (Left) and EER & Power Input over varying indoor temperature (Right) at 35°C outdoor for Voltas fix speed AC

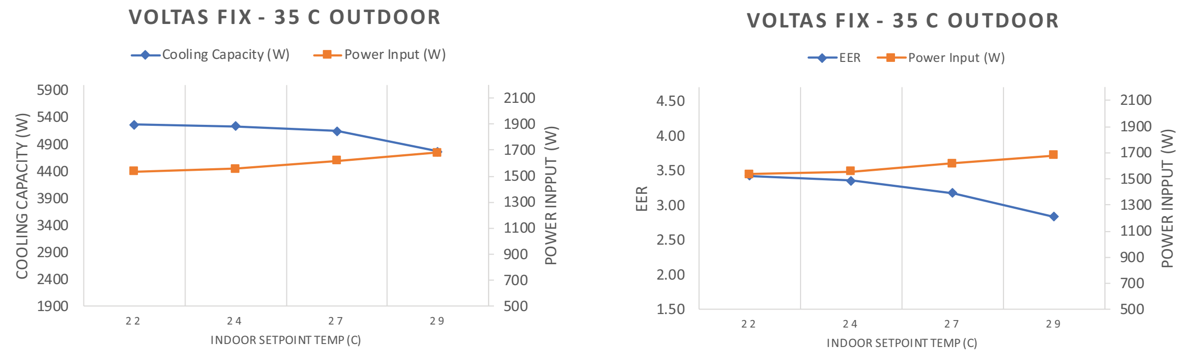


Figure 8: Cooling Capacity & Power Input over varying indoor temperature (Left) and EER & Power Input over varying indoor temperature (Right) at 35°C outdoor for Daikin inverter AC

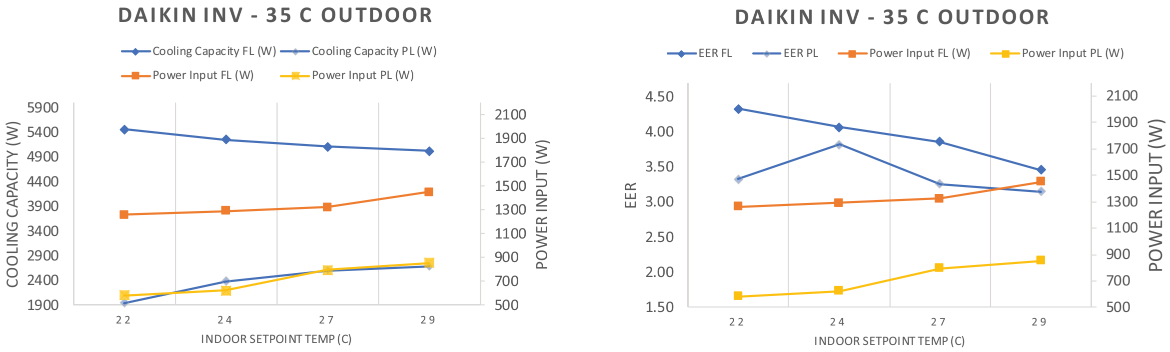
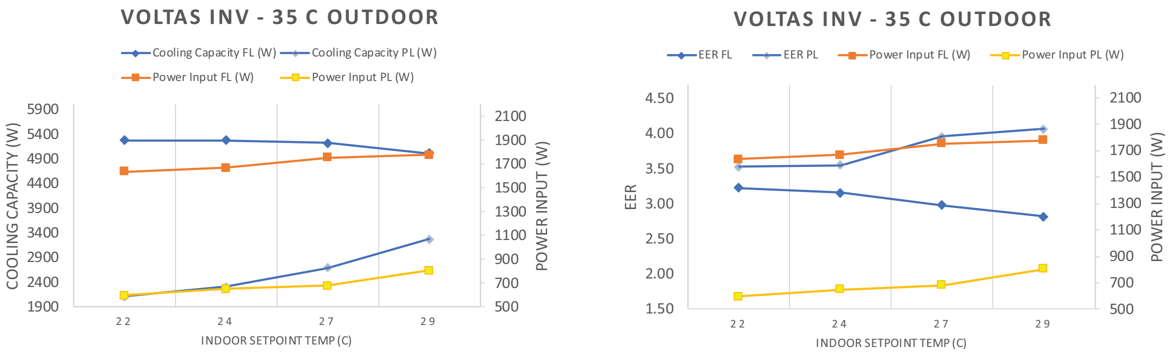


Figure 9: Cooling Capacity & Power Input over varying indoor temperature (Left) and EER & Power Input over varying indoor temperature (Right) at 35°C outdoor for Voltas inverter AC



In addition to the above graphs, the following 5 sets of graphs are also included in the appendix:

- Dedicated plots depicting effect of varying outdoor temperatures on cooling capacity and input power at different indoor set-points.
- The percentage improvement or decrement in cooling capacity compared to rated conditions.
- The percentage improvement or decrement in input power compared to rated conditions.
- The percentage improvement or decrement in EER compared to rated conditions.
- The breakup of total cooling capacity, in terms sensible and latent components, for varying indoor set-point at different outdoor conditions.

The lab tests outcomes show the following:

Effect of indoor set-point variation on Cooling Capacity:

As the indoor set-point is increased, the observed general trend is decrease in cooling capacity of the tested RACs. With 7°C increase in indoor set-point from 22°C to 29°C, the associated impact on cooling capacity of various models, at 35°C outdoor temperature (BEE standard testing condition) is as follows

- For Fixed speed models, the cooling capacity dropped by 3% in Daikin and 9% in Voltas
- For Inverter models at full load, the cooling capacity dropped by 8% in Daikin and 5% in Voltas. At full load conditions the inverter models showed similar trends to those of fix speed models.
- For Inverter models at 50% loading, the cooling capacity increased by 39% in Daikin and 55% in Voltas. At part load conditions the inverter models showed similar trends to those of fix speed models.

Effect of indoor set-point variation on Input Power:

As the indoor set-point is increased, the observed general trend is increase in power draw of the tested RACs. With 7°C increase in indoor set-point from 22°C to 29°C, the associated impact on input power of various models, at 35°C outdoor temperature (BEE standard outdoor testing condition) is as follows

- For Fixed speed models, the input power decreased slightly by 0.3% in Daikin and increased by 9% in Voltas. Although in Daikin fix speed, lowest input power was observed at 27°C indoor set-point.
- For Inverter models at full load, the input power increased by 15% in Daikin and 9% in Voltas. At full load conditions the inverter models showed similar trends to those of fix speed models.
- For Inverter models at 50% loading, the input power increased by 46% in Daikin and 35% in Voltas. At part load conditions the inverter models showed much accentuated increase compared to fix speed models.

Effect of indoor set-point variation on EER:

As the indoor set-point is increased, the observed general trend is decrease in EER of the tested RACs. With 7°C increase in indoor set-point from 22°C to 29°C, the associated impact on EER of various models, at 35°C outdoor temperature (BEE standard outdoor testing condition) is as follows

- For Fixed speed models, the EER decreased by 3% in Daikin and 17% in Voltas. Although in Daikin fix speed, best (highest) EER was observed at 27°C indoor set-point.
- For Inverter models at full load, the EER decreased by 20% in Daikin and 13% in Voltas. At full load conditions the inverter models showed similar trends to those of fix speed models.
- For Inverter models at 50% loading, the EER decreased by 5% in Daikin and increased by 15% in Voltas. At part load conditions, Daikin model showed similar trend but Voltas model showed an inverse trend.

Effect of outdoor temperature variation on Cooling Capacity:

As the outdoor temperature is increased, the observed trend is decrease in cooling capacity of the tested RACs. With 15°C increase in outdoor temperature from 30°C to 45°C, the associated impact on cooling capacity of various models, at 27°C indoor set-point (BEE standard indoor testing condition) is as follows

- For Fixed speed models, the cooling capacity dropped by 24% in Daikin and 32% in Voltas
- For Inverter models at full load, the cooling capacity dropped by 20% in Daikin and 31% in Voltas

Effect of outdoor temperature variation on Input Power:

As the outdoor temperature is increased, the observed trend is increase in input power of the tested RACs. With 15°C increase in outdoor temperature from 30°C to 45°C, the associated impact on input power of various models, at 27°C indoor set-point (BEE standard indoor testing condition) is as follows

- For Fixed speed models, the input power dropped by 34% in both Daikin and Voltas
- For Inverter models at full load, the input power dropped by 24% in Daikin and 18% in Voltas

Effect of outdoor temperature variation on EER:

As the outdoor temperature is increased, the observed trend is decrease in EER of the tested RACs. With 15°C increase in outdoor temperature from 30°C to 45°C, the associated impact on EER of various models, at 27°C indoor set-point (BEE standard indoor testing condition) is as follows

- For Fixed speed models, the EER dropped by 43% in Daikin and 49% in Voltas
- For Inverter models at full load, the EER dropped by 35% in Daikin and 41% in Voltas

The lab tests were aimed to explore the co-relation between the indoor set-point and the energy performance of RACs. The observed general trend of decrease in EER of tested RACs with increase in indoor set-point seems counter-intuitive to the general perception of ATC impact on energy performance. However, this outcome could largely be a reflection of the limitations of the test setup which does not accurately imitate the real world. With regards to the impact of outdoor temperature variation on energy performance of tested RACs, the increase in input power over the operating range (for instance, upto 34% in Daikin fixed speed model) is quite alarming and highlights the importance of ISEER rating which is now being adopted by BEE for all RACs, both fixed speed and inverter types. The former BEE rating of EER does not capture the impact of outdoor temperature variation and speaks only of one outdoor condition, i.e. 35°C.

It is worth underscoring that irrespective of the observed increase in power draw, ATC will result in energy savings, simply because adopting relatively higher set-point temperatures will result in a reduction in the operating time of the RAC units.

Subsequent to the test, we have discussed the outcomes with key industry experts to obtain possible explanations, but at best only have some hypotheses which are discussed in the next section. As such we feel that these test results alone may not be a sound basis to accurately predict the energy performance of RACs at varying indoor conditions. Hence it is critical to conduct further studies to capture transient (real world) operation of air conditioners.

In order to advance this study to its conclusion and to estimate the nationwide savings potential from ATC adoption, we have conducted a simulation as an extra step, to serve as the basis for estimating the savings potential, and this is further discussed in Chapter 5.

4.2. Possible Explanation of the Observed Lab Test Results

4.2.1 Limitation of the lab test conducted at steady state

The lab tests were designed and conducted at steady state conditions (for half an hour duration as aforementioned) which is very different from how air conditioners behave in the real world where both the outdoor as well indoor conditions are always in the transient state due to many factors including- fluctuations in weather conditions, varying internal loads and the very effect of the cooling generated by the air conditioner in the space.

4.2.2 Cooling coil subjected to higher loads with increasing set-point temperature

The increase in power draw when we increase the set-point from 22˚C to 29˚C can be explained by considering the following logic - by raising the set-point in the test chamber, the cooling coil is made to cool air at a higher temperature with higher heat content. Thus, the AC (its compressor) is subjected to a higher load and has to work comparatively more and hence the resultant increased power draw. The decreased cooling capacity with increasing indoor set-point may be attributed to reduced potential to extract latent load from air as we raise the indoor set-point conditions. A closer look at the breakup of total cooling capacity reveals that with increase in indoor set-point, marginal increase in sensible cooling capacity is observed; but the latent cooling capacity reduces considerably thereby resulting in overall cooling capacity reduction. Similar performance trends are observed in full load inverter systems.

4.2.3 Industry hypothesis that the system may be designed for optimal performance at certain outdoor/indoor condition combination

Daikin shows best EER at 27˚C Indoor & 35˚C Outdoor (rated conditions). Daikin also shows sudden decrease in power draw at 27˚C Indoor condition at 30 and 40˚C outdoor conditions as well. This may be attributed to conscious optimization of Input Power (the lower the better) at rated conditions of 27˚C Indoor & 35˚C Outdoor, resulting in optimized (highest) EER.

Endnote

Findings from this lab test exercise should only be viewed as a starting point in the investigation of impact of temperature set-point variation on actual energy performance of different types of room air conditioners. Further studies including in-situ testing of RACs or designing elaborate lab tests to capture transient operation of air conditioner with set-point variation, may either reinforce the observations made, or perhaps show different aspects of the problem. We recommend that more extensive research including in-situ monitoring of select buildings in different climatic zones is required. AEEE is planning to carry out future experimental work on RACs in the ambit of projects that are already well in pipeline.

Considering the gaps observed and emphasized in our explanations, we have designed and conducted energy simulation of both RACs and chillers in residential and commercial buildings to corroborate the results of lab tests which were clearly insufficient for the purpose of this study.

5 SIMULATION

5.1. Methodology for Estimating Energy Savings from ATC through Energy Simulation Approach

As per the scope of this study, it was envisaged to estimate the ATC energy saving potential in RACs through lab tests and commercial building air conditioning systems through secondary research based upon available literature in India. The energy simulation exercise was designed as an alternative to inform the energy saving potential through adoption of ATC in the India context. While energy simulation was not within the scope of this study, a macro level energy simulation exercise was conducted to supplement key data gaps in the available literature and that of the expected lab test outcomes. The four broad activities leading up to estimation of energy saving potential from ATC are summarized in Table below and enumerated thereafter.

Table 10: Methodology for estimating energy savings from ATC

Activity	Approach
Establishing current set-point tendencies	Through surveys
Establishing acceptable ATC set-points	Through surveys and secondary research
Establishing energy saving potential by ATC over current set-points	Through energy simulation
Validation of energy saving potential through secondary research	Based upon available literature in Indian context

5.1.1 Establishing Current Set-point Tendencies-

The first step to predict energy savings from adoption of adaptive thermal comfort is understanding current temperature set-point tendencies across different types of buildings. Table 11 captures the representataive operating set-points for different climatic zones derived from the surveys delineated in Chapter 3.This was accomplished by administering surveys to capture air-conditioning use related information for both residential as well as commercial buildings. Two separate surveys were designed for residential and commercial buildings (Chapter 3) keeping in mind the different drivers that influence set-point propensities. The residential survey targeted individual household owners/ dwellers while the commercial survey targeted real estate facility management firms that operate large portfolio of commercial buildings or in-house facility management teams that manage multiple properties of the group. The willingness as well as barriers to adoption of ATC in commercial buildings were also captured in the commercial building survey. The representative operating set-points for different climatic zones derived from the surveys are tabulated below.

Table 11: Representative operating set-points for different climatic zones

Climatic Zone	Representative Operating (Baseline) Temperature Set-point	
	Residential	Commercial
Warm and Humid	24°C	24±1°C
Composite	22°C	24±1°C
Hot and Dry	24°C	24±1°C

5.1.2 Establishing Acceptable ATC Set-points

After establishing the current set-point temperature, the next step is estimation of acceptable ATC set-points. For residential buildings this was achieved by review of secondary literature (Section 1.2) and for commercial buildings it was captured through surveys (Section 1.3). Considering the complex nature of commercial buildings in terms of different thermal conditions required for various applications, the findings of commercial building survey were also utilised. Based upon the above considerations, the proposed acceptable ATC temperature set-point which are applicable for all climatic zones of India are tabulated below.

Table 12: Proposed ATC Temperature Set-point

Climatic Zone	Proposed ATC Temperature Set-point	
	Residential	Commercial
Warm and Humid	26°C±1°C	26°C
Composite	25°C±1°C	26°C
Hot and Dry	26°C±1°C	26°C

5.1.3 Establishing Energy Saving Potential by ATC over Current Set-points

Energy simulation on EnergyPlus platform was performed to study the impact of temperature set-point on energy performance of air-conditioners. Two separate models were created for residential buildings and commercial buildings having split type AC modelled as PTAC (Packaged Terminal Air Conditioner) and water cooled centralised system respectively. Detailed sensitivity analysis was carried out for each degree increase in set-point from 22°C to 29°C for three different climatic zones of India. The three climatic zones considered in this analysis are: composite (New Delhi), hot and dry (Jodhpur, and warm and humid (Mumbai). The efficiency of split air-conditioners and type of centralised air-conditioner were also varied to study their impact on set-point variation. The simulation model inputs are summarised in Appendix 2. The simulation results on energy consumption reduction with increase in temperature set-point for the three representative climatic zones are summarised in Table 13 below

Table 13: Compilation of percentage energy savings by temperature set-point increase (from energy simulation by AEEE)

Temperature Set-point Change (°C)	Percentage Energy Savings					
	Composite		Warm and Humid		Hot and Dry	
	RAC	Central	RAC	Central	RAC	Central
per °C						
22°C - 23°C	8%	2%	8%	4%	7%	3%
23°C - 24°C	8%	2%	9%	3%	8%	2%
24°C - 25°C	9%	1%	9%	2%	8%	2%
25°C - 26°C	9%	1%	10%	2%	8%	2%
26°C - 27°C	10%	1%	11%	2%	9%	1%
27°C - 28°C	10%	1%	12%	1%	10%	1%
28°C - 29°C	11%	1%	13%	1%	10%	1%
until 25°C						
22°C - 25°C	22%	5%	24%	8%	21%	7%
23°C - 25°C	16%	3%	17%	5%	15%	4%
until 26°C						
22°C - 26°C	29%	6%	32%	10%	28%	9%
23°C - 26°C	24%	4%	26%	7%	22%	6%
24°C - 26°C	17%	3%	19%	4%	16%	3%
until 27°C						
22°C - 27°C	36%	7%	39%	12%	34%	10%
23°C - 27°C	31%	5%	34%	8%	29%	7%

Temperature Set-point Change (°C)	Percentage Energy Savings					
	Composite		Warm and Humid		Hot and Dry	
	RAC	Central	RAC	Central	RAC	Central
24°C - 27°C	25%	3%	28%	5%	23%	5%
25°C - 27°C	18%	2%	20%	3%	17%	3%
until 28°C						
22°C - 28°C	43%	8%	47%	13%	41%	11%
23°C - 28°C	38%	6%	42%	9%	36%	8%
24°C - 28°C	33%	4%	36%	7%	31%	6%
25°C - 28°C	26%	3%	30%	5%	25%	4%
26°C - 28°C	19%	2%	22%	3%	18%	3%
until 29°C						
22°C - 29°C	49%	9%	54%	14%	47%	12%
23°C - 29°C	45%	7%	50%	11%	43%	9%
24°C - 29°C	40%	5%	45%	8%	38%	7%
25°C - 29°C	35%	4%	39%	6%	33%	5%
26°C - 29°C	28%	3%	32%	4%	26%	4%
27°C - 29°C	20%	2%	24%	3%	19%	2%

5.1.4 Validation of energy saving potential by secondary research

A handful of simulation-based studies to explore the impact of set-point variation on energy performance of air conditioners are carried in India. These studies also attempt to correlate the set-point variation with occupants' thermal comfort sensation. Ghawghawe et al. gives a detailed account of the percentage reduction in cooling energy consumption at different temperature set-points for five cities representing different climatic zones of India. This simulation exercise was carried out for an ECBC compliant building with split air-conditioner modelled as PTAC system in Design Builder 3.0.0.104 simulation software. The pertinent results of this study are compiled in Table 14 below.

Dhak[30]a et al. conducted a questionnaire-based evaluation of occupants' thermal comfort sensation and proposed possible energy savings, concurrently achieving optimum thermal comfort for building occupants. Bureau of Energy Efficiency (BEE) star rated office building, in the composite climate of Jaipur having centralised air conditioning system was surveyed and simulated using eQUEST energy simulation software. The proposed temperature of 27.3°C resulted in building energy saving of about 7.86% over base temperature set-point of 20°C. The study outcomes are compiled in Table 14 below.

Table 14: Compilation of percentage energy savings by temperature set-point increase (from research studies in India)

Temperature Set-point Change (°C)	Percentage Energy Saving			
	Composite		Warm and Humid	Hot and Dry
	RAC (Ghawghawe et al.)	Centralised (Dhaka et al.)	RAC (Ghawghawe et al.)	RAC (Ghawghawe et al.)
per °C increase				
20°C - 21°C		0%		
21°C - 22°C		1%		
22°C - 23°C	7%	1%	6%	7%
23°C - 24°C	7%	1%	6%	7%
24°C - 25°C	7%		7%	6%
25°C - 26°C	8%		8%	8%
26°C - 27°C	8%		9%	9%
27°C - 28°C	9%		10%	10%

Temperature Set-point Change (°C)	Percentage Energy Saving			
	Composite		Warm and Humid	Hot and Dry
	RAC (Ghawghawe et al.)	Centralised (Dhaka et al.)	RAC (Ghawghawe et al.)	RAC (Ghawghawe et al.)
until 27.3°C*				
20°C - 27.3°C		8%		
21°C - 27.3°C		7%		
22°C - 27.3°C		7%		
23°C - 27.3°C		6%		
24°C - 27.3°C		5%		

**: Dhaka et al. has proposed an acceptable ATC set-point of 27.3°C for commercial buildings in Composite climatic zone of India.*

Comparison of Table 13 and 14 shows concurrence of AEEE's simulation exercise with other published research studies in India.

5.2. Limitations of a simulation-based approach:

Findings from this simulation exercise should only be treated as a starting point in the investigation of impact of temperature set-point variation on actual energy performance of different types of air conditioners employed in a residential or commercial building. The simulation results presented here are based on generic assumptions of building envelope and occupancy schedules, and a more detailed study may either reinforce the observations made, or perhaps show different aspects of the problem. The authors recommend that more extensive research including in-situ monitoring of selected buildings in different climatic zones is required. In order to address these limitations, investigation not limited to desktop research or lab testing, but also spanning over longer timeframe are obligatory.

5.2.1 Estimation of National Energy Savings from ATC

As per the agreed scope of work for this study, it was envisaged to estimate the ATC energy saving potential in RACs through lab tests and commercial building air conditioning systems through secondary research. However. in the absence of comprehensive literature on the impact of ATC in commercial building air conditioning systems, energy saving estimates based upon simulation have been shown.

The energy saving estimates through adoption of ATC have been determined for three broad categories of air-conditioning systems prevalent in India- RAC, Chiller, and VRF & packaged DX. Findings of the lab tests as well as energy simulation study were employed in the estimation exercise delineated below.

Table 15: Savings Estimation Approach by Technology

Technology	Utilisation	Savings Estimation Approach
RAC	Residential and Commercial Space Cooling	(1) Analytical approach utilising Lab Tests, and (2) Energy Simulation
Chiller System	Commercial Space Cooling	Energy Simulation
VRF and Packaged DX	Commercial Space Cooling	Energy Simulation

5.3. RAC

Two separate approaches were employed to estimate the national energy savings in RACs: Analytical approach utilising Lab Tests and Simulation approach

5.3.1 Analytical Approach Utilising Lab Tests

The starting point of the analysis i.e. the 2030 RAC stock information was realized though a bottom-up approach using sales data mentioned in industry reports and production data published by BEE – this was verified during stakeholder consultations. This total RAC stock was then distributed by climate (composite, hot and dry and warm and humid). Typical tonnage and BEE star-rating were then applied on the RAC stock. The deployed cooling capacity, EER, annual run hours, and capacity factors were used to obtain the annual energy consumption. Table 16 (A&B) presents the key inputs and assumptions used in the RAC analysis, citing their respective sources and basis. As a general protocol, the various assumptions were validated by subject matter experts including industry associations, government agencies, think-tanks and manufacturers. An independent nation-wide survey to map the use of domestic RACs carried out in 2017 by AEEE was used to corroborate several parameters like tonnage, BEE star-rating and annual run-time. An underlying assumption is that the results obtained from the AEEE survey can be applied equally well to RACs used in homes and commercial spaces.[31]

Table 16A: RAC – Key Inputs and Assumptions (Common)

Tonnage	1.5 TR	Production data published by BEE and the AEEE Survey show that 1.5 TR is the most preferred RAC tonnage consumed; studies by LBNL and CEEW also use this tonnage value[32,33]; it is assumed that the popularity of 1.5 TR RACs will continue into the next decade - this has also been suggested in market intelligence reports[34]
BEE star rating	3*	BEE data indicates that 3* RACs are most widely utilized – this has been verified by market intelligence reports and the AEEE Survey; while the same star-rating is assumed as in 2017, it is important note that the ISEER of 3* RACs will improve between now and 2030
Share of Fixed-Speed and Inverter Technologies (2030)	95-100% inverter	Considering the trends in the uptake of fixed-speed and inverter RACs observed in the past few years and similar trends observed in other geographies, it is anticipated that the share of fixed-speed RACs in the future RAC stock will decline rapidly
Outdoor temperature	35	BEE RAC testing standard
EER @ outdoor temperature and set-point	Please see Table 17	These EER were obtained from the psychrometric RAC lab tests results (Chapter 4)
Capacity factor for inverter RACs[35]	Baseline: 70-80% ATC: 60-65%	In the face of no reliable inputs, this is an assumption; this metric deserves more attention and AEEE is committed to exploring this further in future projects and RAC lab tests

Table 16B: RAC – Key Inputs and Assumptions (Climate-wise)

	Warm and Humid	Composite	Hot and Dry	Notes
Stock (million units)	97	83	56	For estimating the 2030 stock, an annual growth of 15% was applied during the years 2018 through 2030, based upon historical growth rates and inputs from industry experts The total stock was distributed climate-wise using the state-wise domestic and commercial electricity consumption reported by the Central Electricity Authority[36]
Neutral temperature range	25.2 – 27.5°C	24.3 – 27.8°C	23.7 – 28.0°C	Dhaka, Mathur and Garg 2012

	Warm and Humid	Composite	Hot and Dry	Notes
RAC stock used below neutral range (i.e. RAC stock eligible for savings from ATC)	80%	37%	21%	Per AEEE RAC survey
RAC stock used in neutral temperature range	16%	43%	34%	
Baseline setpoint (i.e. most preferred setpoint)	24°C	22°C	24°C	
ATC setpoint	27°C	27°C	27°C	Per literature review
Annual runtime (hour)	1421	1635	1355	The annual runtime was informed by the responses gathered by the AEEE survey. Our results are in close alignment with BEE's estimate of 1600 annual run hours used for their calculations.

Table 17: EER (kW/kW) computed through Field Tests

Set-point	EER (kW/kW) at 35°C Outdoor Temperature
22	4.3
24	4.1
27	3.9
29	3.5

5.3.2 Results and Discussion

The stock numbers, EER, annual runtime and compressor factor listed in Table 16 were used to compute the baseline and improved annual energy consumptions. The key results have been tabulated in Table 18.

Table 18: Estimation of national energy savings in RACs by ATC, determined through Lab test enabled analytical approach

Climate Zone	Baseline energy consumption (TWh)	Improved energy consumption with ATC intervention (TWh)	Energy savings (TWh)	Savings potential
Warm and humid	136	125	11	8%
Composite	119	109	10	8%
Hot and dry	81	75	6	7%
Total	336	309	27	8%

The results of the analytical method show national annual energy saving of ~8% i.e. 27 TWh in 2030.

5.3.3 Energy Simulation Approach for RACs

The same baseline set-point temperatures and the corresponding energy consumption for different climatic zones of India, elaborated and quantified in above section 6.1.1 have been considered for energy simulation approach. The possible energy savings by adoption of the suggested adaptive thermal comfort set-point, derived from the energy simulation study have been described in section 5.1.3 of Chapter 5. These % savings are the basis of the calculations presented below in Table 19.

5.3.4 Results and Discussion

The climatic zone wise energy saving potential in RACs, by adoption of adaptive thermal comfort, through energy simulation approach has been tabulated below (Table 19).

Table 19: Estimation of national energy savings in RACs by ATC determined energy simulation approach

Climate Zone	Baseline set-point temperature	Baseline Energy Consumption in 2030 (TWh)	Temperature set-point change	% Savings from set-point change	Improved energy consumption in 2030 with ATC intervention (TWh)	Total Savings Proposed (TWh)
Warm and humid	24°C	136	24 to 27 °C	28%	106	30
Composite	22°C	119	22 to 27 °C	36%	103	16
Hot and dry	24°C	81	24 to 27 °C	23%	77	4
Total		336			286	50

The results of the simulation method show national annual energy saving of 15% i.e. 50 TWh in 2030 with ATC set-point over baseline energy consumption with current set-point tendencies. In our view this may be an overestimation of the real-life potential. A comparison of the national energy saving estimates in RACs through both the approaches, analytical and simulation, exhibit a marked difference with savings from simulation approach being considerably higher than that of analytical approach.

Considering the uncertainties in some of the assumptions of both the methods, the actual energy savings from RACs may lie somewhere in between the two extremes i.e. 27-50 TWh.

5.4. Chiller System

5.4.1 Energy Simulation Approach

To project the energy savings estimate at the national level by 2030, it is imperative to first estimate baseline energy consumption of chillers utilized for space cooling applications in 2030. The estimation of baseline energy consumption in 2030 is done based upon an assessment of total installed capacity, operating system efficiencies and annual run-time of chiller systems. The chiller installed capacity in 2030 was estimated based upon sales data and future growth projections in consultation with industry experts and published research reports. Chiller sales data, sourced from various market intelligence reports (BSRIA Chiller Report[37], 6Wresearch[38]) across different types of technologies has been aggregated from past years. It was observed from BSRIA chiller report that roughly one-sixth of the total annual chiller sales goes into replacing old existing chillers. The future growth in the chiller market which in turn is driven by growth in the retail, hospitality and infrastructure projects has also been forecasted based upon BSRIA reports across different typologies till 2021 and same growth rate has been assumed till 2030 based upon inputs from industry experts. Chiller systems are broadly classified into three type of compressors- Screw Chillers, Scroll Chillers, and Centrifugal Chillers. It is estimated that the total chiller installed capacity will reach 18.5 million TR by 2030 in a BAU scenario.

The overall operating efficiency of the chiller plant including both high side (chiller, chilled water pumps, condenser water pumps, cooling tower) and low side equipment (air handling units, fan coil units) were estimated based upon consultations with HVAC industry peers working in the realms of designing, commissioning, retro-commissioning and retrofitting HVAC systems. The operating efficiencies of different types of chillers have been estimated based upon minimum efficiency standards prescribed in ECBC 2017[39]. Minimum ECBC compliance requirements of IPLV (Integrated Part Load Value) have been considered for the 2017 efficiency levels of chillers. For estimating the future improvements in efficiency of chillers under the BAU scenario, ECBC+ requirements have been considered for the medium-term time horizon by 2030. The minimum energy performance improvement trends of ASHRAE Standard 90.1 from 2004 onwards (2004, 2007, 2010, 2013, 2016) were also studied. It was observed from the past trends that the minimum efficiency requirements of chillers as specified by ASHRAE 90.1 would be at par with ECBC+ requirements by 2027. The efficiency levels of all chiller plant auxiliaries derived from extensive consultations with industry champions and domain experts were aggregated with that of chiller to arrive at the overall chiller plant efficiency. The system efficiency range considered across different type of chillers and their typical capacity ranges are summarized in Table 20.

Table 20: Types of chillers, typical capacity ranges, and overall system efficiency (2030)

Type of Compressor	Typical Capacity Range	Overall System Efficiency
Screw	60 to 570 TR	0.80 to 0.85 kW/TR
Scroll	16 to 60 TR	0.85 to 0.90 kW/TR
Centrifugal	100 to >710 TR	0.75 to 0.85 kW/TR

Annual run-time of 2568 hours was considered based upon 70:30 mix of daytime versus 24-hour buildings in the commercial stock. It has also been assumed that 20% of the total deployed capacity is stand-by and at any given point of time, a maximum of 80% capacity is working. It is estimated that the total energy consumption from chiller system will reach 36.8 TWh by 2030 in a BAU scenario

The total energy consumption in 2030 was then divided into three climate zones (composite, hot and dry and warm and humid) based upon state-wise commercial electricity consumption as reported by CEA. The baseline set-point temperature of 23°C and a proposed ATC set-point temperature of 26°C were considered for the saving estimation (delineated in section 5.1 of chapter 5). The energy saving potential for commercial buildings using centralised air conditioning systems, in terms of percentage energy reduction, through adoption of adaptive thermal comfort (delineated in section 5.1.3 of chapter 5) was utilised to estimate the total energy savings in 2030.

5.4.2 Results and Discussion

The results of the analysis have been tabulated below –

Table 21: Estimation of national energy savings in Chiller by ATC determined through energy simulation approach

Climate Zone	Baseline set-point temperature	Energy Consumption at 23°C in 2030 (TWh)	Temperature set-point change	% Savings from set-point change	Energy Consumption at 26°C in 2030 (TWh)	Total Savings Proposed (TWh)
Warm and humid	23°C	16.0	23 to 26 °C	7%	14.8	1.1
Composite	23°C	11.1	23 to 26 °C	4%	10.7	0.4
Hot and dry	23°C	9.7	23 to 26 °C	6%	9.1	0.6
Total		36.8			34.7	2.1

The results of the simulation method show national annual energy saving of 6% i.e. 2.1 TWh in 2030 in chiller systems with ATC set-point over baseline energy consumption. The energy saving potential in chiller systems is considerably lower compared to RACs. This may be attributed to the fact that with standard HVAC control systems, the sensitivity of temperature set-point largely affects and most of the time remains limited to the air handling units (AHU) only. AHUs generally constitute around 20% (or less) of the overall chiller system energy consumption. As elaborated in Chapter 5, the energy saving potential in chiller systems determined through the energy simulation exercise was consistent with other secondary literature available on similar studies in India. The findings were even validated in stakeholder consultations conducted during the commercial building survey.

5.5. VRF and Packaged DX System

For estimating the baseline energy consumption in 2030, first the total VRF and Packaged DX installed capacity in 2030 was obtained from various published research reports and interaction with equipment manufacturers. The VRF and Packaged DX sales from past years was obtained from market intelligence reports (BSRIA, CEEW).

For VRF systems, an annual growth rate of 15% is forecasted by BSRIA till 2020; HVAC industry experts suggest that the VRF market will grow at the same rate for the next decade. Based on tonnage, VRF systems were classified into mini VRF (5 TR) and large VRF (11TR), of which large VRF system is dominant in the commercial market. It is estimated that the total installed capacity will reach 15 million TR by 2030 in a BAU scenario. The rated efficiency of VRF systems ranges from 0.8 to 1.1 kW/TR depending upon equipment size. As per ECBC-2017[39], the minimum efficiency requirement for VRF systems (< 40 kW) is 0.81 kW/TR. In the BAU scenario, this efficiency is assumed until 2030, assuming a higher degree of code compliance in commercial buildings in the next decade.

The market size of packaged DX systems in 2017-18 is estimated to be around 0.6 million TR and is anticipated to grow at a CAGR of 5% in the next decade. As per BSRIA, there is minimal growth in ducted and small packaged DX and the market size of rooftop DX is very small. Also, growth of indoor packaged unit is decreasing, as VRFs continue to grow. As per ECBC-2017, the minimum efficiency requirement for an air-cooled packaged DX system (<10.5 kW) is 1.25 kW/TR. In the BAU scenario, it is estimated that by 2030 the efficiency of packaged DX will reach around 1.1 kW/TR, which is the minimum efficiency requirement for an ECBC+ compliant building i.e. an energy efficiency improvement of 13% over 2017 baseline level. This is in line with trends in ASHRAE standards of minimum cooling efficiency for packaged AC.

An annual replacement factor of 10% was assumed to calculate the stock numbers an annual run-time of 1920 hour was considered based daytime application in commercial building to estimate the annual energy consumption. It is estimated that by 2030 in a BAU scenario, the total energy consumption will reach will 23 TWh and 16 TWh for VRF and Packaged DX systems respectively.

Any technical literature on the energy consumption impact of change in temperature set-point for VRF and packaged DX systems in India could not be found. For estimating the energy savings at the national level in 2030, we have made a conservative assumption that the minimum energy savings attainable shall be equivalent to at least that of chiller systems utilised in the commercial buildings. The savings potential can be further refined in future studies with deeper stakeholder outreach and/or detailed energy simulation studies.

5.5.1 Results and Discussion

The results of the analysis have been tabulated below –

Table 22: Estimation of national energy savings in VRF and Packaged DX systems by ATC determined through energy simulation approach

Climate Zone	Baseline set-point temperature	Energy Consumption at 23°C in 2030 (TWh)	Temperature set-point change	% Savings from temperature set-point change (23-26°C)	Energy Consumption at 26°C in 2030 (TWh)	Total Savings Proposed (TWh)
VRF						
Warm and humid	23°C	9.9	23 to 26 °C	7%	9.2	0.7
Composite	23°C	6.9	23 to 26 °C	4%	6.7	0.3
Hot and dry	23°C	6.0	23 to 26 °C	6%	5.7	0.4
Sub-total		22.9			21.6	1.3
Packaged DX						
Warm and humid	23°C	7.0	23 to 26 °C	7%	6.5	0.5
Composite	23°C	4.9	23 to 26 °C	4%	4.7	0.2
Hot and dry	23°C	4.2	23 to 26 °C	6%	4.0	0.3
Sub-total		16.1			15.2	0.9
Total		**39.0**			**36.7**	**2.3**

The results for VRF and Packaged DX system show national annual energy saving of 2.3 TWh in 2030 with ATC set-point over baseline energy consumption with current set-point tendencies.

5.6. Summary of Results

The overall energy savings potential in RACs, chillers and VRF system in 2030 is tabulated below –

Table 23: Summary of national energy savings potential in RACs, chillers and VRF and Packaged DX systems in 2030

Component	Climatic zone wise national energy savings (TWh)			Total national energy savings (TWh)
	Warm and humid	Composite	Hot and dry	
RACs	11-30	10-16	4-6	27-50
Chiller system	1.1	0.4	0.6	2.1
VRF system	0.7	0.3	0.4	1.3
Packaged DX	0.5	0.2	0.3	0.9
Total	13-32	11-17	5-7	31-54

The results of nationwide impact of ATC adoption show 8%-13% reduction potential in the energy required for air-conditioning. This equates to an energy saving potential of 31-54 TWh in 2030 over the projected energy consumption with current set-point tendencies.

Relative to the respective energy consumption, RACs show maximum savings potential from ATC, as compared to the savings possible in chillers, VRF and Packaged DX systems. The available secondary literature also highlights that the savings potential in RACs is considerably higher.

6 EVALUATION OF CURRENT POLICY FRAMEWORK

This chapter collates and evaluates existing policy options including building codes and guidelines for realising energy savings using adaptive thermal comfort and related interventions. The focus is on capturing operational practices mentioned by the codes and guidelines which have the potential to save energy from set-point increase.

6.1. ECBC 2007[39]

Launched in 2007, the Energy Conservation Building Code (ECBC) was an unprecedented initiative by Bureau of Energy Efficiency (BEE) to address energy management in large commercial buildings. There are two ways to demonstrate ECBC compliance: (a) Prescriptive approach and (b) Whole Building approach. ECBC 2007 refers to NBC ventilation guidelines for naturally ventilated buildings but it does not recommend any set-points based on climatic conditions. The whole building compliance approach suggests set-points while modelling and simulating cooling load and enabling the economizer by adjusting the lockout control; however, the adaptive thermal comfort theory for achieving optimum comfort and maximising energy savings was introduced in its 2017 version.

6.2. ECBC 2017[40]

Launched in 2017, this new version of ECBC delineates principles of adaptive thermal comfort and provides a methodology for calculating operating temperatures for naturally ventilated, mixed mode and air-conditioned buildings.

6.3. ECBC-R[41]

The ECBC-Residential (R) (Part 1) draft shared in the public domain in early 2018, focuses on minimising heat transfer through the building envelope to achieve comfortable indoors. However, the code does not explicitly outline any set-point ranges.

6.4. NBC 2016[42]

Part 8 – Building Services of NBC 2016 Volume 2, Section 3 - Air Conditioning, Heating and Mechanical Ventilation, highlighted that the primary objective of designing indoor environments is to ensure thermal comfort of all occupants. The Code discussed designing indoor conditions per the adaptive thermal comfort model: "Air conditioning systems for interior spaces intended for human occupancy shall be sized for not more than 26°C for cooling at occupied level". The Code provides a methodology for naturally ventilated, mixed mode and air-conditioned buildings.

6.5. ISHRAE[43]

The Indian Society of Heating, Refrigerating & Air-conditioning Engineers (ISHRAE) databook 2017 is the most recent version of HVAC handbook released by ISHRAE to address various HVAC requirements specifically in the Indian context. The handbook provides comprehensive information on designing of HVAC along with introduction to green buildings and relevant IS and international codes & standards. The databook doesn't delve into operations guidelines and thus there is not mention of thermal comfort band for Indian climatic zones and application of ATC.

6.6. CPWD General Specifications for HVAC Works 2017[44]

CPWD HVAC specs document is a revised version of specifications released in 2004. It recommends cooling demand density based on ASHRAE GRP 158, Load Calculation Manual (Heating & Cooling), and provides the recommended cooling demand densities (m^2/TR) for different building types using air conditioning systems. The manual also lists Building Management Systems for Air-conditioning applications only; however, the thermal comfort conditions for different climate zones are not indicated and applications of adaptive thermal comfort theory to maximise energy savings is missing.

6.7. NDC[45]

The country's Nationally Determined Contribution (NDC) within the Paris Agreement framework enlists enhancing energy efficiency as one of the mitigation strategies through BEE's Standards and Labelling Programme and energy-efficient buildings through building code compliance. Incorporating the adaptive thermal comfort model guidelines to HVAC operations in building code norms and its stringent compliance will help advance the country's international commitments.

6.8. BEEP Guidelines for Energy-Efficient Multi-Storey Residential Buildings[46,47]

Acknowledging India's rapid growth, pace of urbanisations and increasing demand for housing, these guidelines were developed to mainstream thermally comfortable energy efficient housing stock for different climates for India. The guideline provides comprehensive information on building massing, spatial configuration, building envelope, natural ventilation, appliances, common services and renewable energy integration. Extensive multi-storey residential sector case studies and surveys were conducted to understand design configuration and to monitor electricity consumption which supports the study recommendations. The guidelines were developed for agencies/persons involved in the regulation, design, and construction of multi-storey residential buildings in urban areas and would also be of interest to home buyers, home occupants, and users too. The guidelines recommend raising the cooling set-point as part of natural ventilation and space cooling strategy. Raising the cooling set-point from 24 °C to 28 °C (~adaptive comfort temperature for summer as per ASHRAE 55) can bring ~55%–60% reduction in cooling demand.

6.9. Standards & Labelling Programme[48]

The programme was launched to address the varying energy demand of the products from different manufactures. A key objective of the programme is to provide consumer a platform listing energy consumption and savings opportunity of various appliances, helping them to have an informed choice. The programme could also explore advocating savings from adaptive thermal comfort by providing information on the energy label indicating the potential energy savings which can be achieved if user adapts to higher set-points.

6.10. Summary

It is evident from the current policy framework and other prescriptive guidelines that adaptive thermal comfort is recognised as a definitive means of cutting down energy consumption from air-conditioning use. ECBC 2017 alludes to the principles of adaptive thermal comfort and provides a methodology for calculating operative temperatures for different building types; similarly, the BEEP guidelines for large residential buildings prescribe energy savings from raising set-points. However, whilst these are applaudable mentions, there is a clear lack of emphasis on achieving optimum comfort and maximising energy savings from adaptive thermal comfort; moreover, there is little consensus of optimum set-points for different building types in different climate zones. This leaves for much future recommendations and actions.

7 FUTURE RECOMMENDATIONS

There is a clear case for the effectiveness of ATC as a viable strategy to address the escalating energy needs for cooling the building sector in India and bringing meaningful energy savings. Based on our learnings from the literature review as well as our surveys, and our review of the existing policy framework and the gaps therein with respect to ATC, we see three core areas that can promote the adoption of ATC and help manifest the nationwide savings potential. These are:

- Establishing a concept of comfort-temperature range and ensuring its integration in the building codes
- Operational interventions
- User awareness and messaging to promote the concept of ATC

Our recommendations organized within these three broad areas are as follows:

1. Integrating Comfort-Temperature Range in Building Codes & Design Guidelines

a. Establish comfort-temperature ranges which are specific to Indian climate types, as well as building types: Through concerted study of Indian thermal comfort standards, optimum set-points for different building types in different climate zones should be established in our building codes.

   A case in point is our Residential Survey highlighting that more than 80% of the population in warm and humid climate sets their RAC temperatures at or below 24°C. Indian households in this climate-zone have a distinct preference for lower temperature settings in response to the humidity factor.

b. Aligning applicable building code and bye-laws with adaptive comfort standards: Indian energy code, building code and building bye-laws should promote ATC guidelines post occupancy.

c. During building construction, the design guidelines for the HVAC systems should be based on a comfort-temperature range per the ATC standards.

2. Operational Interventions

Residential & Commercial Buildings

a. Promote ATC through Standards and Labelling (S&L) program: The equipment energy consumption labels for RACs should include information on a range of comfort-temperatures and their corresponding annual energy use. This will help sensitize the users towards savings possible through incremental temperature changes and the adoption of ATC. The Bureau of Energy Efficiency (BEE) energy star labelling program (on-going) is well recognised and accepted program amongst the users and leveraging the same platform can help promote adoption of ATC.

   While this strategy is targeted at the residential sector, it would apply to RACs users in commercial buildings as well.

b. Promoting ATC through green building rating systems HVAC O&M compliance criterion: Green building rating systems post occupancy compliance check should consider inclusion of “display of adaptive thermal comfort band ranges” in the buildings. This visibility would promote sensitization towards ATC practices.

Commercial Buildings Only

a. Integrate ATC guidelines in HVAC Operations and Maintenance (O&M) protocol: Include information on adaptive thermal comfort band ranges and corresponding energy savings within the building as part of O&M guidelines.

The standard operating procedures of building operators and facility managers should emphasise achieving optimum comfort and maximising energy savings from adaptive thermal comfort

b. We recommend mandatory inclusion of ATC guidelines in HVAC O&M manual of Public Works Department (PWD) at centre and state level, and Public Sector Undertaking (PSUs) engaged in real estate development and construction (such as National Buildings Construction Corporation Limited (NBCC) guidelines).

3. User Awareness & Promotion of ATC

a. Foster user awareness: Leverage different media platforms such as print, TV, digital etc. and generate awareness on acceptable comfort range and promoting adoption of ATC similar to India's other national program like LED (UJALA scheme), LPG (Ujjwala Yojana) etc. which gained wide traction and quick adoption. Projects that have successfully adopted ATC standards, such as the Delhi Metro, should be highlighted through Government fact-sheets and publications.

b. Endorse energy savings through ATC as national agenda (by promoting programs/ inclusion in India's national and international goals)

    i. SDG 7: Addressing issue of energy access by saving energy from adoption of ATC

    ii. Nationally Determined Contributions (NDC): India's NDC highlights energy efficiency in building sector as an important climate change mitigation strategy. Enhancing energy savings by inclusion of ATC guidelines in commercial and residential building should be once amongst many strategies highlighted in the NDC.

    iii. SE4ALL – Promoting sustainable energy for all by reducing cooling demand through ATC

8 APPENDIX

8.1. Appendix 1 – Commercial Survey Questions

Table 24: Appendix 1 – Commercial Survey Questions

Q#	Question	Description
1	Details of the different types of commercial buildings managed by your facility.	To comprehend the weightage of commercial facilities handled viz Hospitals, Hotels, Institutions, Offices and Retail spaces and analyse the typical EPI (Energy Performance Index) of these spaces.
2	Details of the different types of HVAC systems/configurations installed in these buildings.	To assess and analyse what are the preferred HVAC installation types. Respondents are asked to choose and weigh from Central air cooled, Central water cooled, Packaged and Unitary systems
3	HVAC systems represent what percentage of the total building energy consumption within buildings managed by your facility in both fully air-conditioned (FA) and mixed mode buildings (MM)?	To analyse the typical HVAC energy consumption and its impact in FA and MM buildings.
4	Please indicate the operating hours of HVAC systems for respective building types and climate.	To understand typical operating and usage patterns in FA and MM building types.
5a	Please indicate the typical set-point temperatures maintained during operational hours for different types of buildings.	This forms the crux of the survey to map various adopted set-point temperatures across various building types.
5b	What temperatures are maintained during non-operational hours for different types of buildings?	To accommodate those facilities/spaces which are still conditioned during non-occupancy.
6	Does your HVAC O&M manual specify HVAC set-points for following parameters against different climates and building types?	To identify various adopted standards and verify their compliance with ASHRAE or equivalent standards.
7	Does your HVAC operating manual lists set-point temperature based on adaptive thermal comfort model?	To enquire about the FMs extant knowledge and awareness on ATC.
8a	Do HVAC operations schedules allow for changes in set-point temperatures per user requirement? What protocol do you follow to change the temperature set-point per user requests?	To analyse the operational procedures to meet timely demands of the patrons.
8b	Do you think it is difficult from an O&M PoV to give users the ability to adjust set-points?	To assess feasibility, when patrons can exercise control over thermostat.
8c	How often is the temperature changed as per user-requirement?	To understand the flexibility offered by FMs over occupants' preferences.
9	Do you typically have a Building Management System (BMS) to control the temperature set-points in different spaces?	To assess BMS penetration.
10	Do you typically keep a daily log of temperature and RH maintained in different spaces?	This is linked to Q. 15a
11	How comfortable are occupants with the facility's current set-point temperatures?	To analyse the occupants' acceptability without compromising on the thermal comfort. To analyse the occupants' acceptability without compromising on the thermal
12	On scale of 1 to 5 (with 5 being the most likely), please indicate occupants' willingness to accept a temperature increase of: (a) 1°C (b) 2 °C (c) > 2 °C	
13.	How often do you solicit feedback on occupants' thermal comfort?	
14.	Is it feasible to compensate an increase in set-point by increasing local air movement without compromising on the occupants' thermal comfort? How would they respond?	

Q#	Question	Description
15a	What measures have you introduced in the recent past to manage/ reduce cooling demand in your projects, and what was the outcome?	To assess various energy saving measures adopted in buildings.
15b	What role do building occupants play in this energy management	To analyse occupant behaviour.
16	Do you align HVAC operation schedules with Demand Response programmes offered by DISCOMS?	

8.2. Appendix 2 - Simulation model input for establishing energy saving potential by ATC

Table 25: Appendix 2 - Simulation model input for establishing energy saving potential by ATC

	Residential	Non-Residential
Project Area		
Total Floor Area [m2]	9590	13783
Conditioned Floor Area [m2]	6092	9169
Envelope		
WWR	49%	39%
Window U-Value [W/m2-K]	5.7	2.0
SHGC	74%	37%
VLT	65%	35%
Wall-Above Grade [W/m2-K]	2.8	1.3
HVAC Details		
HVAC System	PTAC	VAV
Building Operation	168 [hr/week]	80 [hr/week]

ANNEXURE

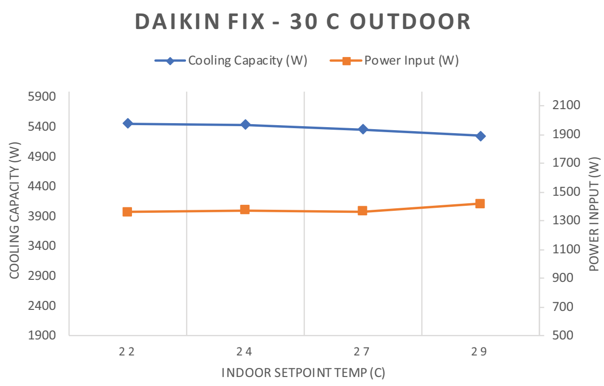
9 ANNEXURE

9.1. Annexure 1A - Full load capacity tests

Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Daikin Fixed speed AC	1.5 TR	5 Star	IS 1391

Table 26: Annexure 1A - Full load capacity tests

Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Test unit measurements										Electrical data measured				
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	DBT (°C) (leav-ing)	WBT (°C) (leav-ing)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measure-ments (m^3 / h)	Tested total ca-pacity (Watt)	Tested Sen-sible capacity (Watt)	Tested Latent ca-pacity (Watt)	Dehumid-ification capacity (Litre / h)	Tested EER (Watt / Watt)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequen-cy (Hz)
1	22	59	16	30	50	21	10	9	18.2	0.9	928.4	5459	3676	1782	2	4.0	228.89	6	0.98	1360.53	49.98
2	22	60	16	35	45	24	10	9	17.8	0.9	927.7	5321	3528	1793	2	3.6	229	6.5	0.98	1470.47	49.98
3	22	59	16	40	48	29	11	10	17.2	0.9	930.2	5124	3368	1755	2	3.2	228.97	7.16	0.98	1626.8	49.98
4	22	61	16	45	43	32	12	11	14.0	0.9	932.2	4158	3072	1086	1	2.4	229.02	7.69	0.98	1745.16	49.99
5	24	54	17	30	49	21	11	10	18.2	0.9	928.1	5440	3845	1595	2	4.0	229.09	5.97	0.98	1373.76	49.98
6	24	55	17	35	44	24	11	11	17.6	0.9	933.4	5269	3775	1494	2	3.6	228.88	6.47	0.98	1482.2	49.98
7	24	55	17	40	49	29	12	11	16.8	0.9	934.5	5020	3599	1421	2	3.1	229.1	7.24	0.98	1640.26	49.98
8	24	56	17	45	45	32	13	12	13.9	0.9	934.8	4111	3190	921	1	2.3	229.18	7.89	0.98	1814.13	49.98
9	27	51	19	30	58	23	14	13	18.1	0.9	931.5	5356	3976	1380	2	3.9	229.02	6.21	0.98	1366.14	49.98
10	27	51	19	35	45	24	14	13	17.8	0.9	937.2	5261	3954	1306	2	3.7	229.33	6.54	0.98	1433.81	49.98
11	27	52	19	40	44	28	15	14	16.8	0.9	935.2	4962	3759	1203	2	3.1	229.18	7.17	0.98	1615.49	49.98
12	27	52	19	45	46	32	16	15	14.0	0.9	926.7	4081	3419	662	1	2.2	229.13	8	0.98	1832.93	49.98
13	29	51	21	30	56	22	16	15	18.0	0.9	927.0	5252	3907	1345	2	3.7	228.85	6.38	0.98	1420.13	49.98
14	29	51	21	35	48	25	16	15	17.5	0.9	933.6	5143	3850	1293	2	3.5	228.95	6.65	0.98	1474.31	49.98
15	29	51	20	40	56	31	16	16	16.0	0.9	931.3	4672	3717	956	1	2.8	229.16	7.25	0.98	1673.56	49.98
16	29	51	21	45	40	31	17	16	13.9	0.9	934.3	4063	3481	582	1	2.2	229.24	8.17	0.98	1875.1	49.98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Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
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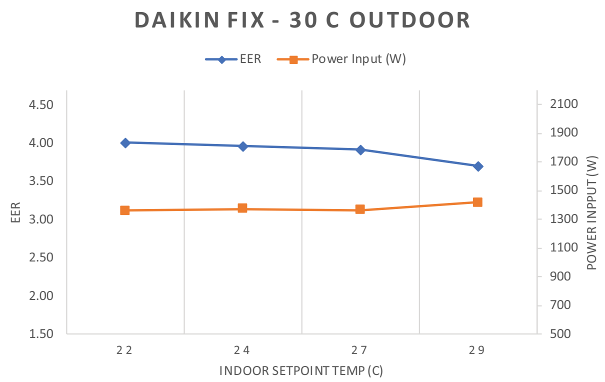
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)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EER
Power Input (W)
EER
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POWER INPPUT (W)
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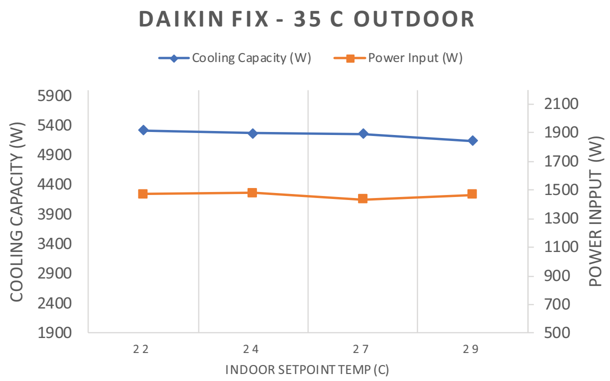
22 24 27 29
INDOOR SETPOINT TEMP (C)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Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
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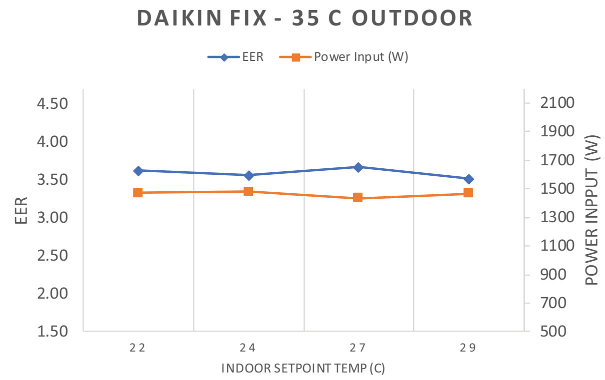
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)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EER
Power Input (W)
EER
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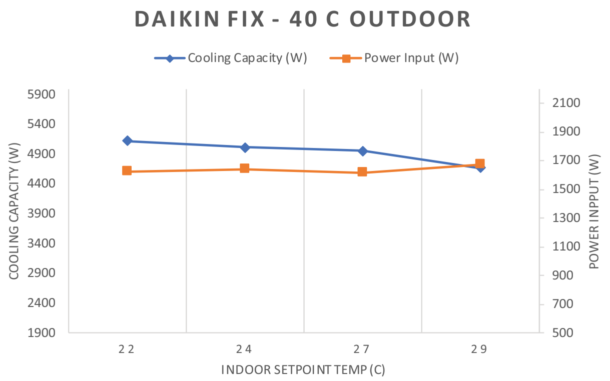
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN FIX - 40 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
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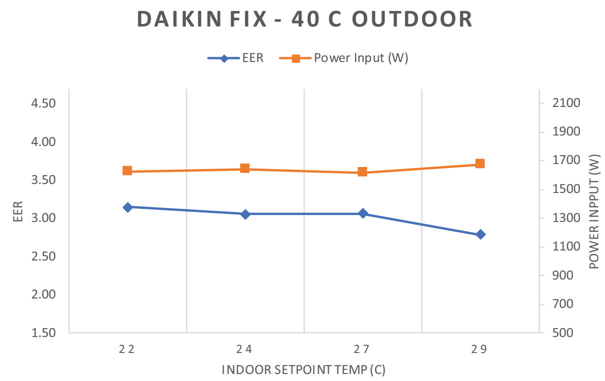
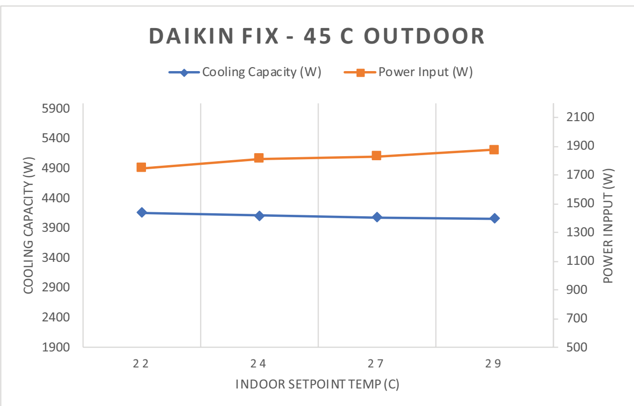
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN FIX - 40 C OUTDOOR
EER
Power Input (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN FIX - 45 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
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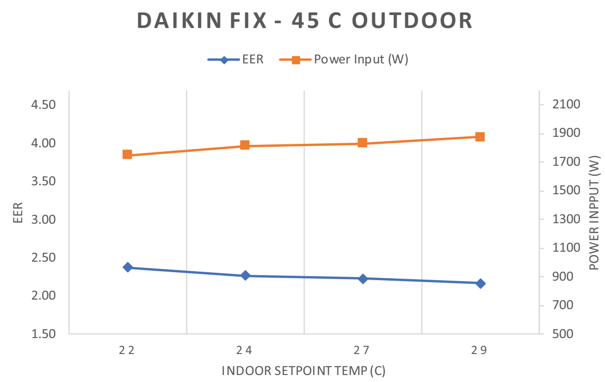
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)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EER
Power Input (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)

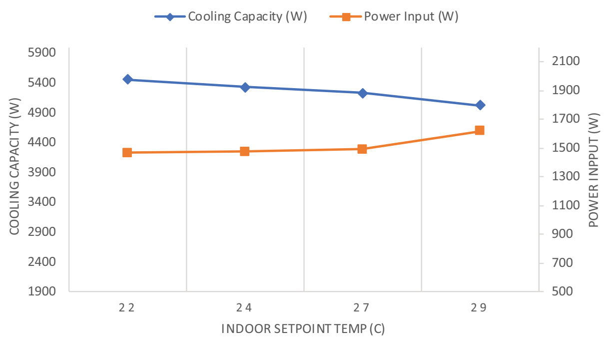
9.2. Annexure 1B - Full load capacity tests

Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Voltas Fixed speed	1.5 TR	3 Star	IS 1391

Table 27: Annexure 1B - Full load capacity tests

Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Electrical data measured					Test unit measurements									
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequency (Hz)	DBT (°C) (leaving)	WBT (°C) (leaving)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measurements (m^3 / h)	Tested total capacity (Watt)	Tested Sensible capacity (Watt)	Tested Latent capacity (Watt)	Dehumidification capacity (Litre / h)	Tested EER (Watt / Watt)
1	22	60	16	30	59	23	229	6	1	1465	50	9.5	8.5	20	1	845	5456	3406	2050	3	3.7
2	22	60	16	35	44	24	229	7	1	1519	50	10	9	19	1	847	5265	3290	1975	3	3.4
3	22	60	16	40	49	29	229	7	1	1677	50	10	9	18	1	846	4926	3215	1712	2	2.9
4	22	60	16	45	42	31	229	8	1	1771	50	12	11	14	1	853	3905	2768	1137	2	2.2
5	24	55	17	30	61	23	229	7	1	1476	50	11	10	19	1	851	5327	3551	1776	2	3.6
6	24	55	17	35	41	23	230	7	1	1557	50	11	10	19	1	843	5234	3491	1743	2	3.4
7	24	55	17	40	49	29	229	8	1	1714	50	13	11	16	1	853	4348	3156	1714	2	2.5
8	24	55	17	45	43	32	229	8	1	1914	50	13	12	14	1	847	3758	2944	814	1	2.0
9	27	51	19	30	55	22	229	7	1	1491	50	14	12	19	1	846	5230	3655	1575	2	3.5
10	27	52	19	35	44	24	229	7	1	1618	50	14	13	19	1	851	5145	3584	1565	2	3.2
11	27	52	19	40	60	32	229	8	1	1764	50	15	14	16	1	849	4243	3319	926	1	2.4
12	27	52	19	45	50	33	229	9	1	1991	50	16	15	13	1	845	3582	3079	508	1	1.8
13	29	51	21	30	58	23	229	7	1	1615	50	16	15	19	1	845	5029	3595	1434	2	3.1
14	29	51	21	35	46	24	229	7	1	1682	50	16	15	18	1	846	4770	3535	1236	2	2.8
15	29	51	21	40	55	30	229	8	1	1830	50	17	16	15	1	852	4094	3336	764	1	2.2
16	29	51	21	45	54	35	229	10	1	2189	50	18	17	13	1	854	3386	3098	293	0	1.6

VOLTAS FIX - 30 C OUTDOOR



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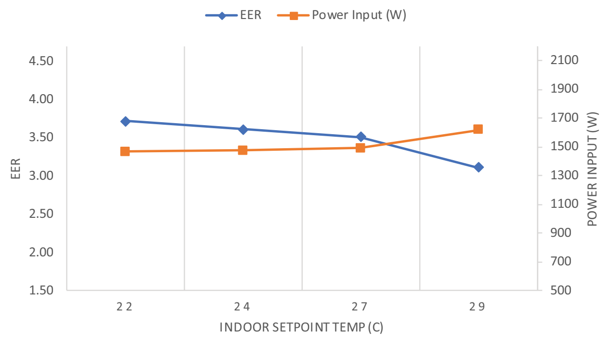
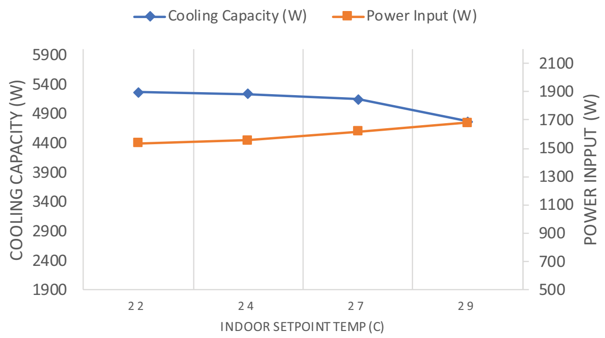
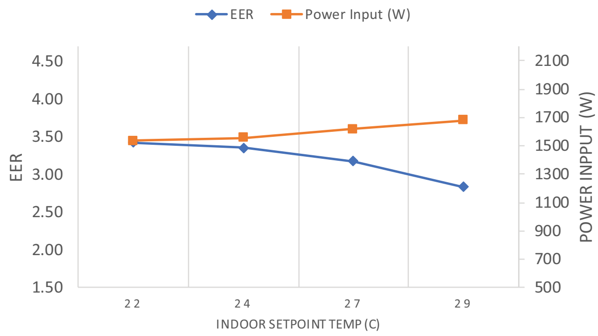


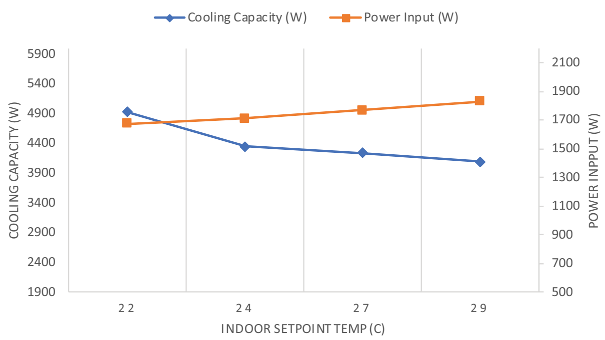
VOLTAS FIX - 35 C OUTDOOR



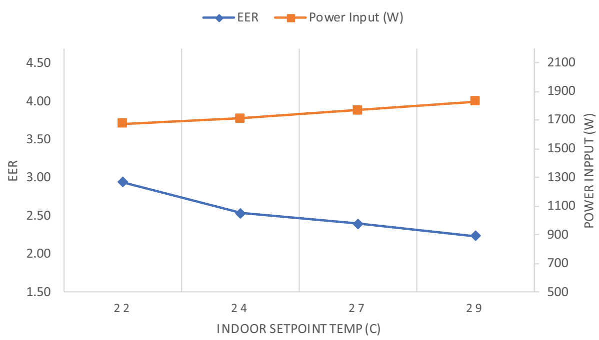
VOLTAS FIX - 35 C OUTDOOR



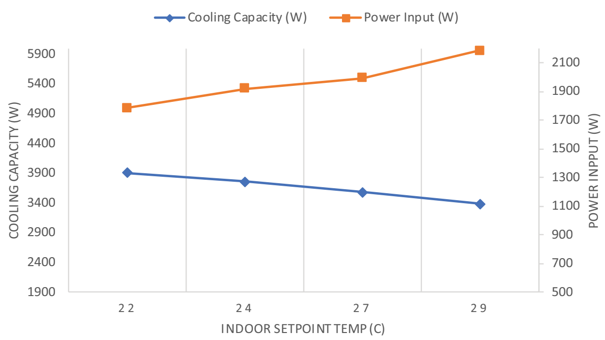
VOLTAS FIX - 40 C OUTDOOR



VOLTAS FIX - 40 C OUTDOOR



VOLTAS FIX - 45 C OUTDOOR



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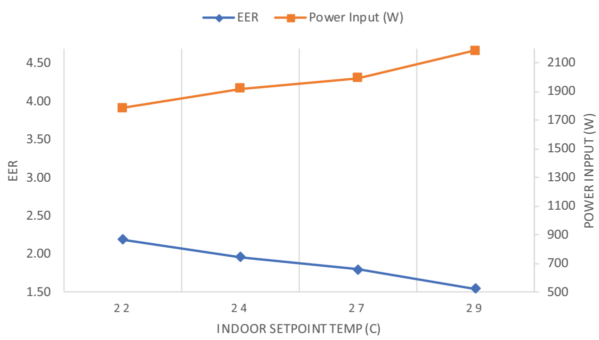
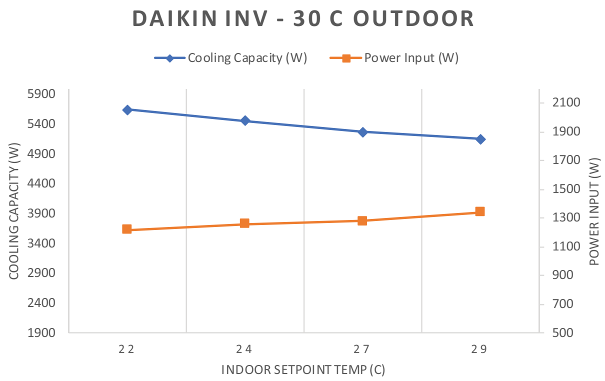


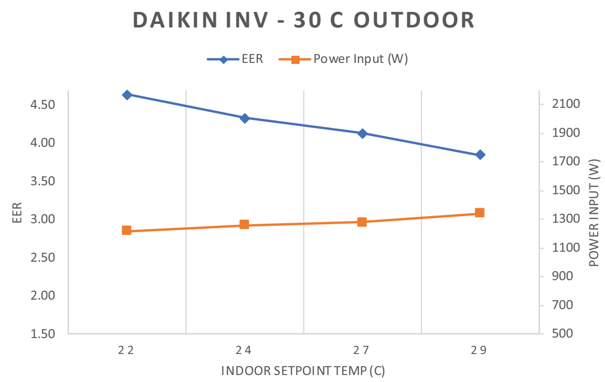
9.3. Annexure 1C - Full load capacity tests

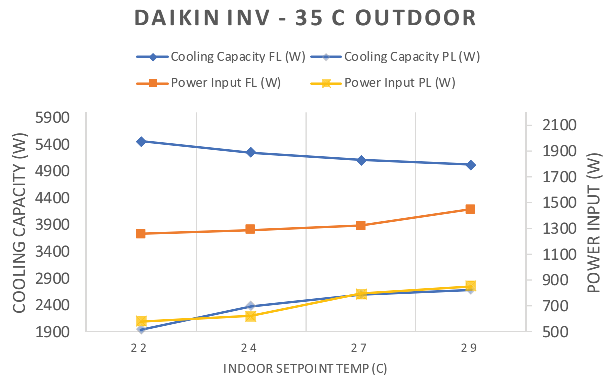
Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Daikin Inverter AC	1.5 TR	5 star	IS 1391

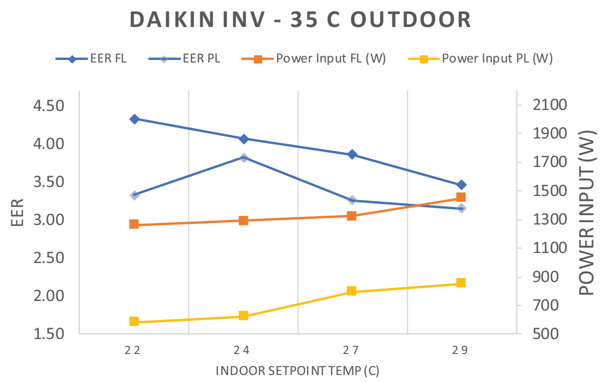
Table 28: Annexure 1C - Full load capacity tests

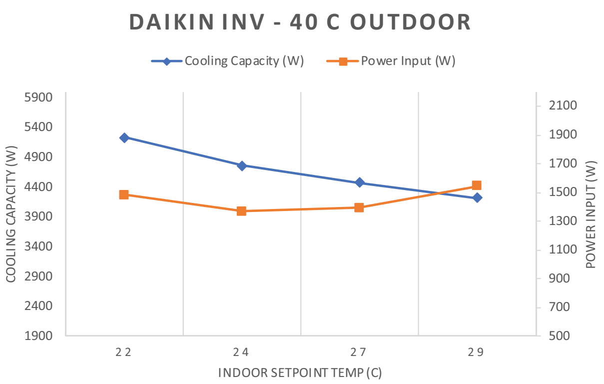
Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Electrical data measured					Test unit measurements									
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequency (Hz)	DBT (°C) (leaving)	WBT (°C) (leaving)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measurements (m^3 / h)	Tested total capacity (Watt)	Tested Sensible capacity (Watt)	Tested Latent capacity (Watt)	Dehumidification capacity (Litre / h)	Tested EER (Watt / Watt)
1	22	59	16	30	58	23	228.74	5.43	0.99	1218.66	49.99	9	8	20	1	856	5649	3580	2068	3	4.6
2	22	59	16	35	52	22	228.45	5.57	0.91	1260.57	49.99	10	9	20	1	853	5457	3489	1968	3	4.3
3	22	60	16	40	44	28	227.75	6.56	0.91	1481.55	50.01	10	9	18	1	874	5236	3462	1774	2	3.5
4	22	59	16	45	39	30	228.96	6.97	0.91	1509.57	50	10	10	17	1	852	4649	3180	1469	2	3.1
5	24	54	17	30	51	22	228.63	5.56	0.99	1259.67	50	11	10	19	1	884	5455	3771	1684	2	4.3
6	24	55	17	35	54	24	228.53	5.76	0.99	1290.37	50	11	10	18	1	889	5249	3678	1572	2	4.1
7	24	55	17	40	48	29	228.8	6.46	0.99	1369.17	50	12	11	17	1	862	4758	3453	1305	2	3.5
8	24	55	17	44	43	31	228.92	7.11	0.99	1259.23	50	12	11	17	1	852	4569	3309	1259	2	2.9
9	27	52	19	30	44	20	228.88	5.76	0.98	1277.7	50	13	12	20	1	840	5276	3690	1586	2	4.1
10	27	52	19	35	44	24	228.96	5.87	0.98	1326	50	14	13	19	1	843	5115	3598	1517	2	3.9
11	27	52	19	40	54	30	228.96	6.41	0.99	1393.44	50	15	14	16	1	866	4481	3415	1065	1	3.2
12	27	55	19	45	45	32	228.81	7.35	0.98	1583.28	50	15	14	16	1	858	4244	3169	1075	1	2.7
13	29	51	20	30	49	30	228.68	6.74	0.99	1341.35	50.02	15	15	19	1	856	5158	3700	1458	2	3.9
14	29	51	20	35	44	24	228.75	7.13	0.85	1449.66	50.01	16	15	19	1	848	5022	3613	1409	2	3.5
15	29	51	20	40	52	30	228.87	7.45	0.99	1545.23	50.01	16	16	16	1	862	4217	3432	785	1	2.7
16	29	51	20	45	45	32	228.87	7.81	0.99	1664.33	50.01	17	16	15	1	856	3905	3286	619	1	2.4

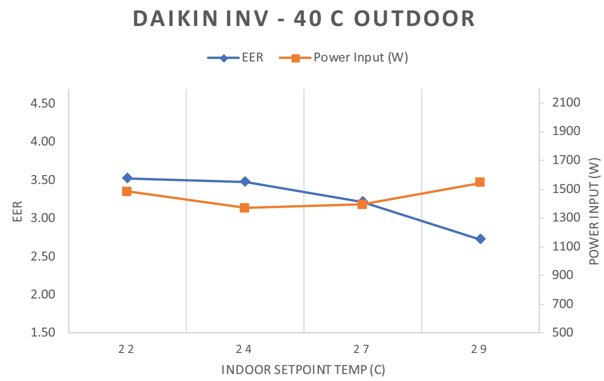

DAIKIN INV - 30 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
5900 5400 4900 4400 3900 3400 2900 2400 1900
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)

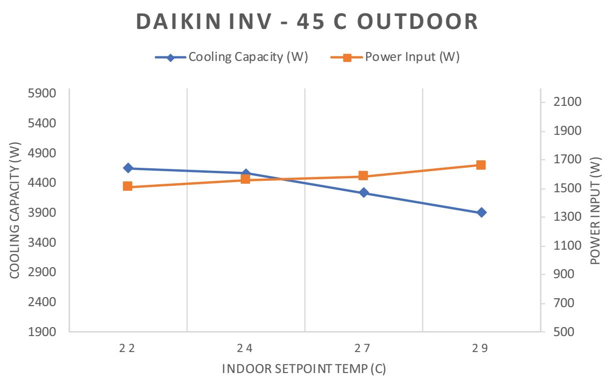

DAIKIN INV - 30 C OUTDOOR
EER
Power Input (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)

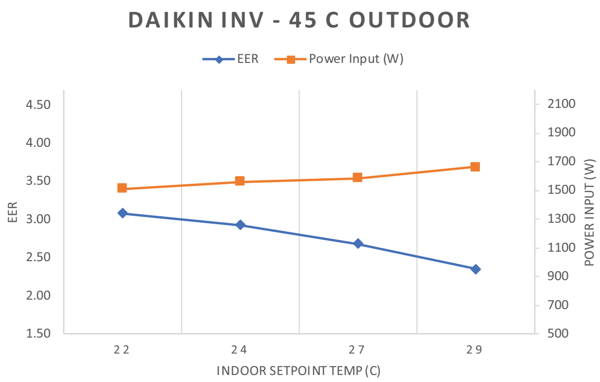

DAIKIN INV - 35 C OUTDOOR
Cooling Capacity FL (W)
Cooling Capacity PL (W)
Power Input FL (W)
Power Input PL (W)
COOLING CAPACITY (W)
5900 5400 4900 4400 3900 3400 2900 2400 1900
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN INV - 35 C OUTDOOR
EER FL
EER PL
Power Input FL (W)
Power Input PL (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN INV - 40 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
5900 5400 4900 4400 3900 3400 2900 2400 1900
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN INV - 40 C OUTDOOR
EER
Power Input (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)


DAIKIN INV - 45 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
5900 5400 4900 4400 3900 3400 2900 2400 1900
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)

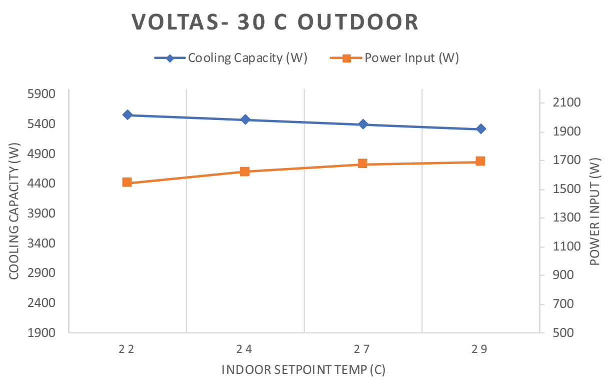

DAIKIN INV - 45 C OUTDOOR
EER
Power Input (W)
EER
4.50 4.00 3.50 3.00 2.50 2.00 1.50
POWER INPUT (W)
2100 1900 1700 1500 1300 1100 900 700 500
22 24 27 29
INDOOR SETPOINT TEMP (C)

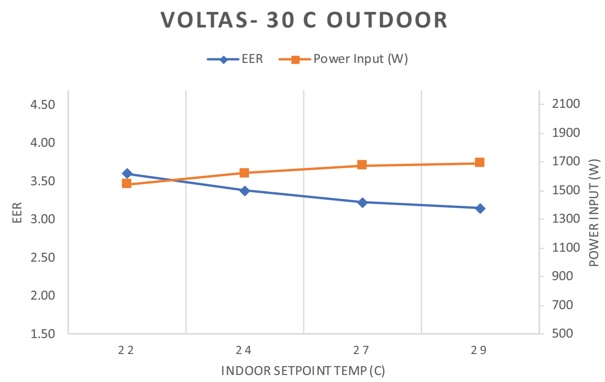
9.4. Annexure 1D - Full load capacity tests

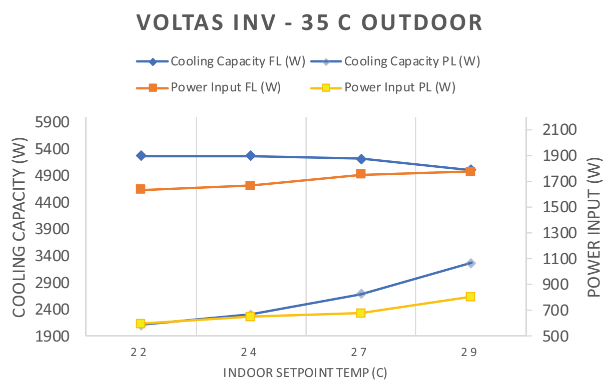
Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Voltas Inverter AC	1.5 TR	3 star	IS 1391

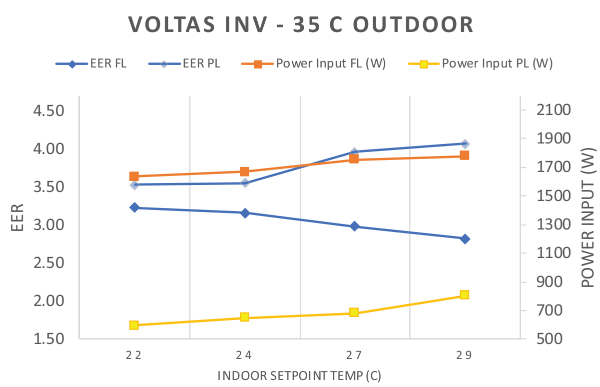
Table 29: Annexure 1D - Full load capacity tests

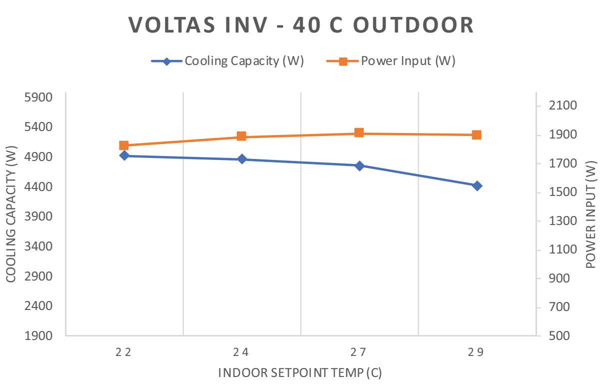
Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Electrical data measured					Test unit measurements									
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequency (Hz)	DBT (°C) (leaving)	WBT (°C) (leaving)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measurements (m^3 / h)	Tested total capacity (Watt)	Tested Sensible capacity (Watt)	Tested Latent capacity (Watt)	Dehumidification capacity (Litre / h)	Tested EER (Watt / Watt)
1	22	59	16	30	51	21	228.38	6.75	0.91	1541.41	49.99	9	8	21	1	837	5556	3526	2029	3	3.6
2	22	59	16	35	44	24	228.35	7.15	0.91	1634.2	49.99	10	9	19	1	846	5281	3380	1901	3	3.2
3	22	59	16	40	45	28	228.25	7.98	0.91	1821.42	49.98	11	9	18	1	851	4924	3200	1724	2	2.7
4	22	59	16	45	36	30	228.26	8.99	0.91	1870.82	49.99	12	11	15	1	840	4041	2830	1212	2	2.2
5	24	55	17	30	54	21	228.02	7.65	0.91	1619.15	49.99	11	10	20	1	840	5480	3584	1896	3	3.4
6	24	55	17	35	44	24	228.18	7.99	0.91	1667.76	49.98	11	10	19	1	846	5273	3541	1732	2	3.2
7	24	55	17	40	47	28	228.29	8.88	0.91	1888.59	49.99	12	11	18	1	845	4866	3354	1512	2	2.6
8	24	55	17	44	47	32	228.3	9.23	0.91	1938.88	49.99	13	12	14	1	857	3887	3026	862	1	2.0
9	27	51	19	30	46	20	228.43	7.87	0.91	1675.13	49.99	13	12	20	1	845	5404	3728	1676	2	3.2
10	27	52	19	35	44	24	228.26	8.34	0.91	1753.17	49.99	14	13	19	1	846	5225	3629	1596	2	3.0
11	27	52	19	40	52	30	228.09	9.21	0.91	1908.53	49.98	14	13	18	1	851	4759	3447	1312	2	2.5
12	27	52	19	45	38	30	228.11	9.45	0.91	1980.6	49.98	16	15	14	1	852	3737	3104	633	1	1.9
13	29	51	21	30	44	20	228.1	7.86	0.91	1689.71	49.99	15	14	20	1	858	5326	3771	1555	2	3.2
14	29	51	21	35	40	23	228.2	8.17	0.91	1776.96	49.99	16	15	19	1	850	5015	3628	1387	2	2.8
15	29	51	21	40	39	27	228.15	9.33	0.9	1901.63	49.99	17	15	16	1	856	4426	3411	1015	1	2.3
16	29	51	21	45	46	32	228.11	1995.39	0.9	1995.39	49.99	18	17	13	1	865	3622	3131	492	1	1.8

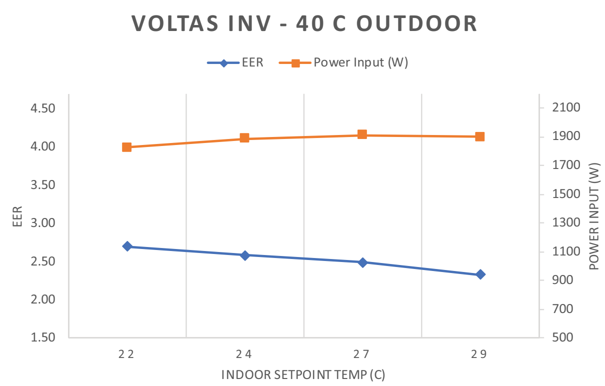

VOLTAS- 30 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)

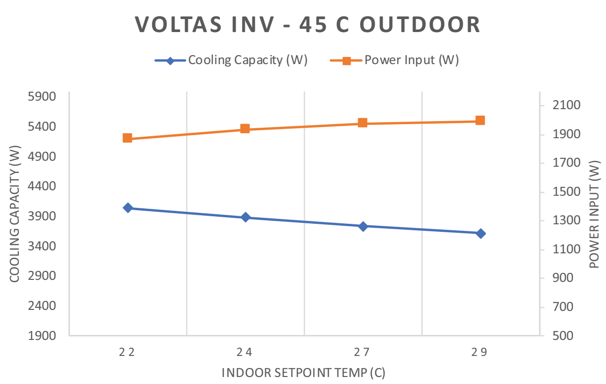

VOLTAS- 30 C OUTDOOR
EER
Power Input (W)
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)

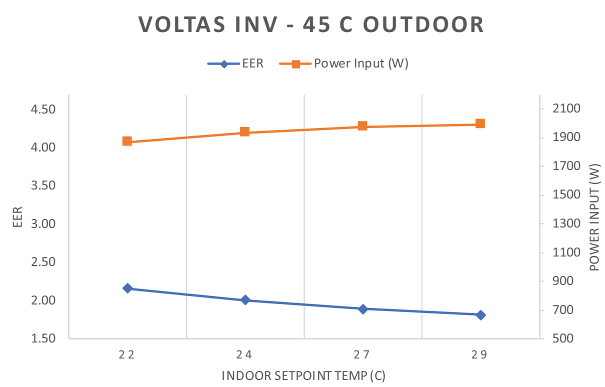

VOLTAS INV - 35 C OUTDOOR
Cooling Capacity FL (W)
Cooling Capacity PL (W)
Power Input FL (W)
Power Input PL (W)
COOLING CAPACITY (W)
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)


VOLTAS INV - 35 C OUTDOOR
EER FL
EER PL
Power Input FL (W)
Power Input PL (W)
EER
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)


VOLTAS INV - 40 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)


VOLTAS INV - 40 C OUTDOOR
EER
Power Input (W)
EER
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)


VOLTAS INV - 45 C OUTDOOR
Cooling Capacity (W)
Power Input (W)
COOLING CAPACITY (W)
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)


VOLTAS INV - 45 C OUTDOOR
EER
Power Input (W)
EER
POWER INPUT (W)
INDOOR SETPOINT TEMP (C)

9.5. Annexure 2A - Part load test results

Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Daikin Inverter AC	1.5 TR	5 Star	Part load capacity

Table 30: Annexure 2A - Part load test results

Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Electrical data measured					Test unit measurements									
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequency (Hz)	DBT (°C) (leaving)	WBT (°C) (leaving)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measurements (m^3 / h)	Tested total capacity (Watt)	Tested Sensible capacity (Watt)	Tested Latent capacity (Watt)	Dehumidification capacity (Litre / h)	Tested EER (Watt / Watt)
1	22	59.86	16.11	35.11	43.87	23.99	711.96	2156.41	3.69	14.06	13.04	14.06	13.04	8.7	0.88	764.52	2122.71	1945.16	177.55	0.2	3.63
2	24.03	54.52	17.02	35.01	44.37	24.01	714.55	2644.07	4.24	14.3	13.37	14.3	13.37	10.62	0.89	768.13	2602.15	2385.78	216.36	0.23	4.17
3	27.09	51.74	19.1	35.11	43.88	23.99	720.18	2737.27	3.43	16.53	15.61	16.53	15.61	11.04	0.89	773.39	2694.48	2599.35	95.12	0.07	3.38
4	28.97	50.91	20.49	35.11	45.97	24.43	721.95	2882.93	3.37	17.96	17	17.96	17	11.64	0.9	775.32	2837.87	2695.06	142.8	0.11	3.32

9.6. Annexure 2B - Part load test results

Tested AC :	Tonnage :	BEE star rating :	Testing standard :
Voltas Inverter AC	1.5 TR	3 Star	Part load capacity

Table 31: Annexure 2B – Part load test results

Sr. No.	Indoor set-point conditions			Outdoor set-point conditions			Electrical data measured					Test unit measurements									
	DBT (°C)	RH (%)	WBT (°C)	DBT (°C)	RH (%)	WBT (°C)	Voltage (Volts)	Current (Ampere)	Power factor	Power (Watts)	Frequency (Hz)	DBT (°C) (leaving)	WBT (°C) (leaving)	Enthalpy Diff. (kJ/kg)	Specific volume (m^3 / kg)	Air flow measurements (m^3 / h)	Tested total capacity (Watt)	Tested Sensible capacity (Watt)	Tested Latent capacity (Watt)	Dehumidification capacity (Litre / h)	Tested EER (Watt / Watt)
1	22.02	60.02	16.12	35.03	44.37	24	228.58	3.21	0.81	597.37	49.99	13.19	12.27	10.83	0.88	609.7	2108.69	1726.65	382.04	0.49	3.53
2	24.02	54.66	17.03	35.02	44.26	24	228.64	3.43	0.81	648.85	50	13.96	12.94	11.82	0.89	610.69	2305.05	1964.44	340.61	0.42	3.55
3	27	52.32	19.08	35.06	44.28	23.99	228.52	3.57	0.81	680.1	50	15.79	14.58	14	0.9	606.6	2690.18	2151.27	538.91	0.67	3.96
4	29.05	51.14	20.53	35.01	44.45	23.97	228.58	4.04	0.9	804.65	49.99	16.07	15.2	17.33	0.9	599.01	3275.11	2453.78	821.33	1.05	4.07

9.7. Annexure 3 – Description of test facility

The test facility can test RACs rated up to 3 Ton nominal cooling capacity. The chamber can maintain 0 to 60 °C air temperature inside the indoor and outdoor compartments. The chamber instruments consisted of controlled power supply system, testing panels, water, and refrigerant flow rate measurements, and code tester. The chamber also contained a network of sensors with 1/10 DIN accuracy (± 0.03 °C). The power measurement instruments at the facility had an accuracy of ± 0.5%. A code tester as shown in following figure 10 was used to measure the volumetric flow rate.

Figure 10: Picture of Code tester: Air flow measurement apparatus

The accuracy of the sensors used for the measurements are in accordance with the standards and are summarized in Table 32:

Table 32: Accuracy and resolution of measuring instruments

Sr. No.	Type of measurement	Sensor type	Range	Accuracy
1	Temperature	PT 100	-	± 0.3 °C
2	Static pressure	Transducer	-2.5 to 2.5 mbar	± 0.25 %
3	Barometric pressure	-	-10 to 10 mbar	± 0.25 %
4	Nozzle differential pressure	-	0 to 20 bar	± 0.25 %
5	Power measurements	Power analyzer	0 to 7.5 kW	± 0.3 %

9.7.1 Calculations for tests

The enthalpy values, relative humidity and specific volume of air are derived using psychrometric equations.

The flow rate was calculated using the nozzle apparatus using the following equation:

$$Volumetric\ Flow\ rate, Q\left(\frac{m^3}{s}\right) = k * C_d * A * \sqrt{h_p * V'_n}$$

Where k (constant) = 1.41,
C_d is the nozzle discharge coefficient (fixed for a nozzle, known value),
A is the area of the nozzle,
h_p is the nozzle differential pressure measured,
V'_n is the specific volume of nozzle inlet air, defined as:

$$V'_n = \frac{P_0}{P} * \left(\frac{V_n}{1+K}\right)$$

Where, P_0 is standard barometric pressure,
P is the barometric pressure at nozzle inlet,
K is specific humidity at nozzle inlet,
V_n is the specific volume of humid air at DBT and WBT existing at nozzle inlet at standard barometric pressure.

The total cooling capacity (CC_T) which is the sum of sensible and latent loads is computed by the following equation.

$$CC_T\ (total) = Q * \rho * (h_{in} - h_{out})$$

where Q is the volumetric flow rate (m^3/s), is the density (kg/m^3) and h is the enthalpy (kJ/kg) and subscripts in, out denote inlet and outlet respectively.

The sensible cooling capacity (CC_S) is computed by the following equation

$$CC_S(sensible) = Q * \rho * (T_{in} - T_{out})$$

where Q is the volumetric flow rate (m^3/s), is the density (kg/m^3) and T is the temperature (°C) and subscripts in, out denote inlet and outlet respectively.

The latent cooling capacity (CC_L) is computed by the following equation.

$$CC_S(sensible) = Q * \rho * (T_{in} - T_{out})$$

The dehumidifying capacity is computed by the following equation.

Where AH denotes Absolute humidity (kg/kg), Q is the volumetric flow rate (m^3/s), is the density (kg/m^3) and subscripts in, out denote inlet and outlet respectively.

The energy efficiency ratio is the ratio of the total cooling capacity (watt) to the electrical power consumed by the RAC (watt) and is computed by the following equation.

$$CC_S(sensible) = Q * \rho * (T_{in} - T_{out})$$

9.7.2 Effect on Cooling capacity and input power at varying outdoor temperatures for different indoor set-points

The cooling capacity and input power draw at various indoor conditions for varying outdoor conditions for Daikin fixed-speed and Voltas Inverter are illustrated in Figure 11 and Figure 12.

Figure 11: Cooling Capacity & Input Power of Daikin fixed-speed, at different indoor set-points over varying outdoor temperatures.

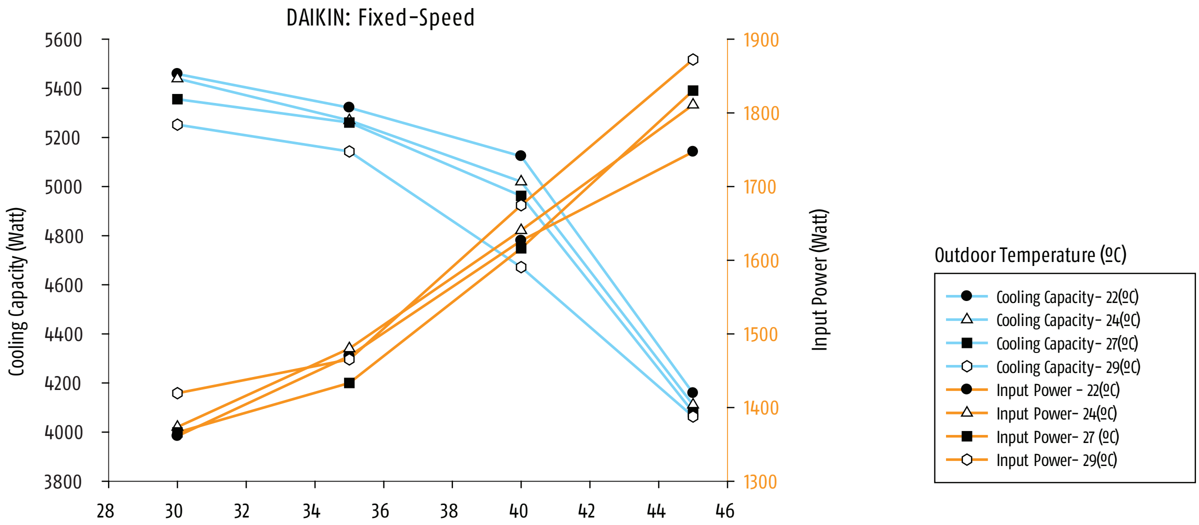
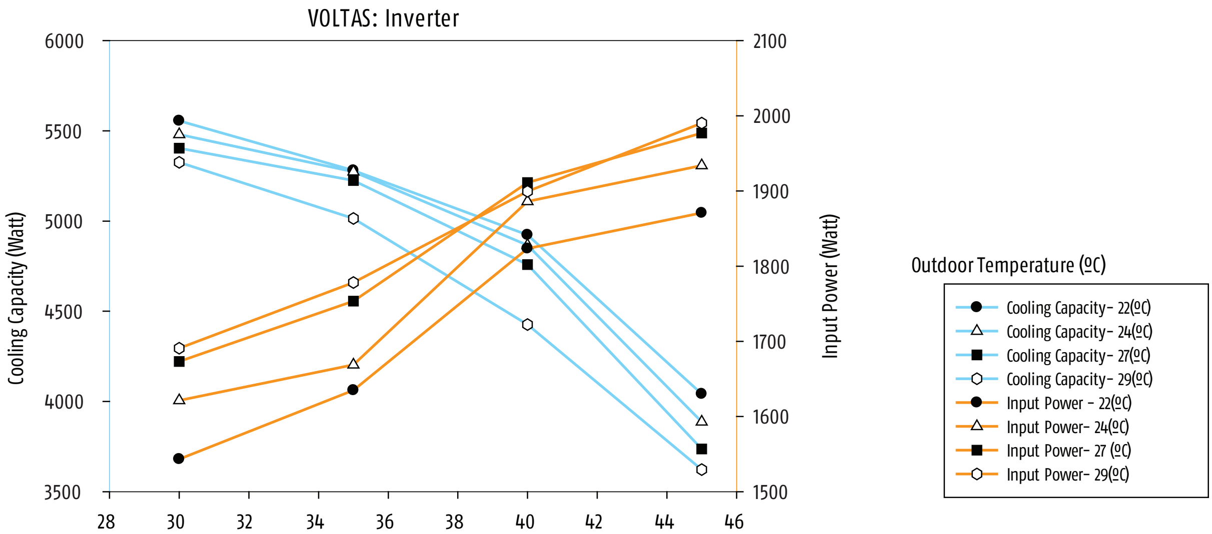


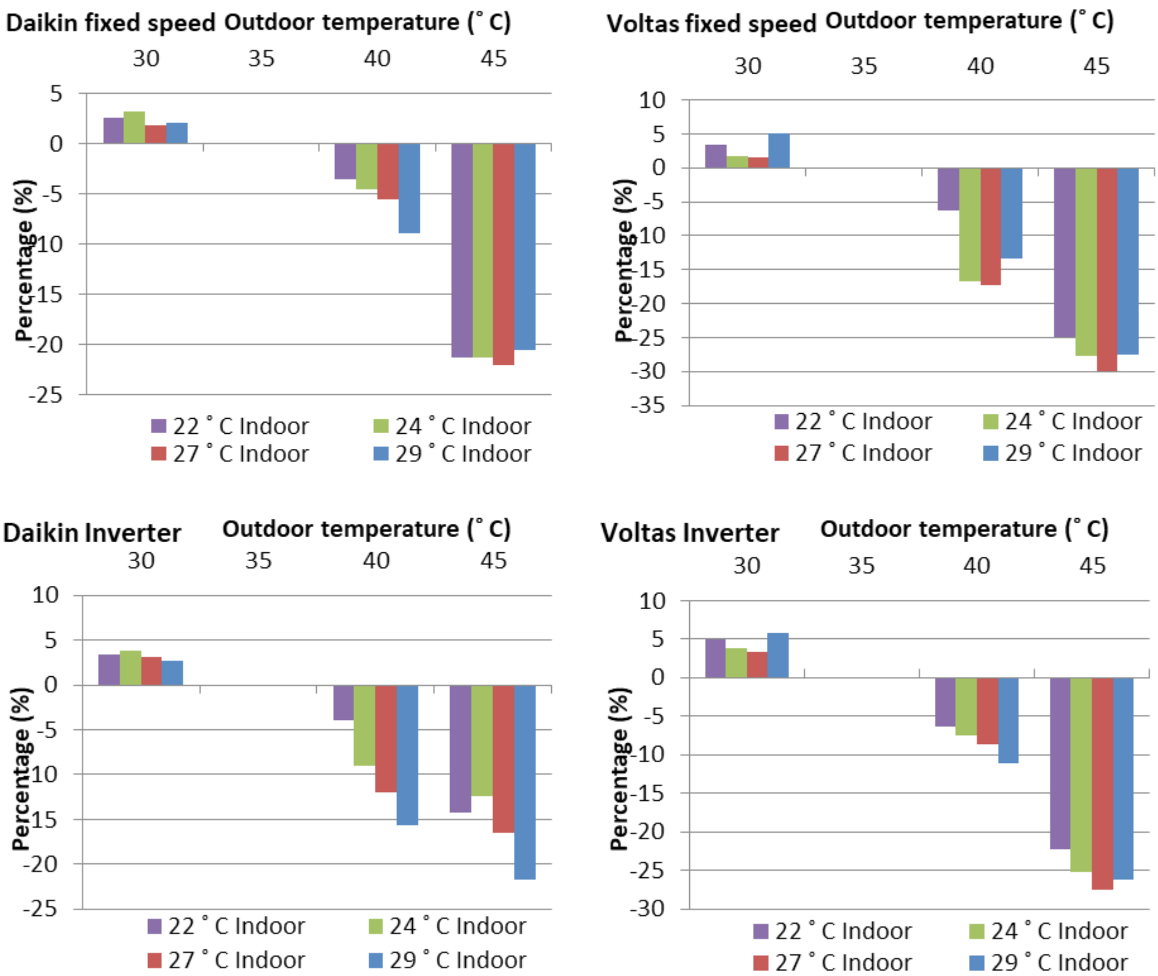
Figure 12: Cooling Capacity & Input Power of Voltas Inverter, at different indoor set-points over varying outdoor temperatures



9.7.3 Effect on cooling capacity

The cooling capacity decreases with increase in the outdoor temperature. Figure 13 illustrates the percentage improvement or decrement in cooling capacity of all the tested RACs at different controlled conditions.

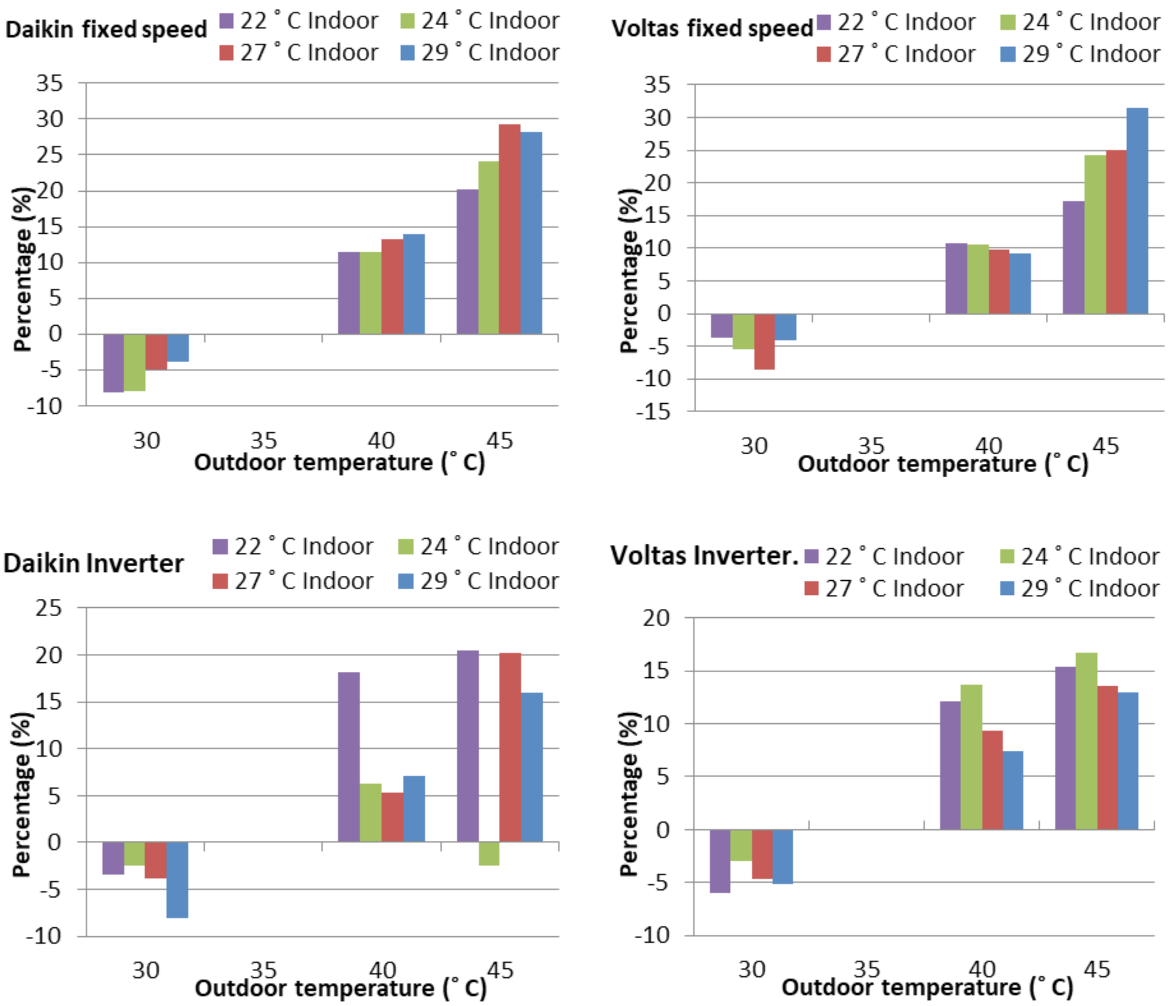
Figure 13: The percentage improvement or decrement in cooling capacity compared to rated conditions



9.7.4 Effect on Input Power

The input power increases with increase in the outdoor temperature. Figure 14 illustrates the percentage improvement or decrement in input power of all the tested RACs at different controlled conditions.

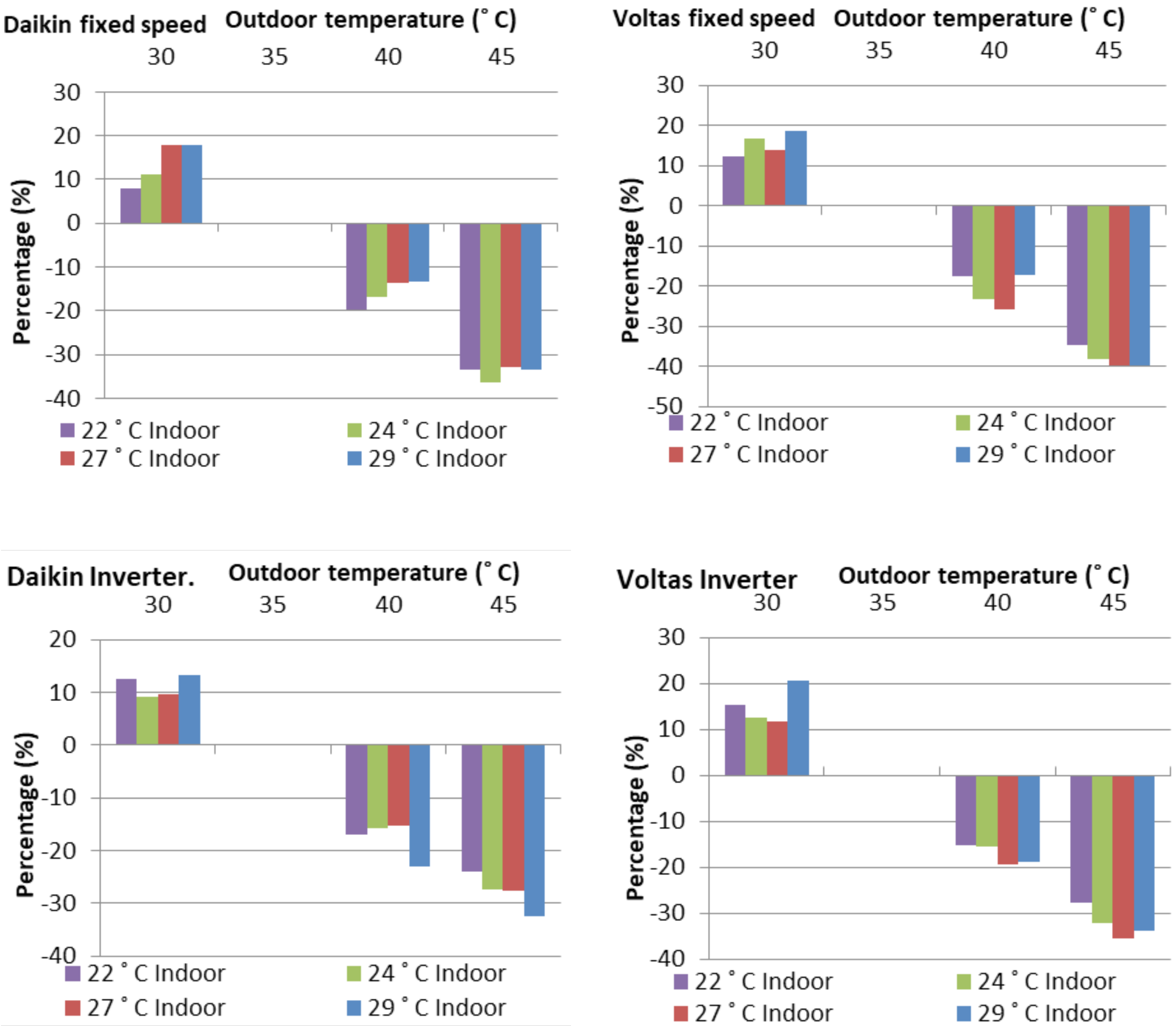
Figure 14: The percentage improvement or decrement in input power compared to rated conditions



9.7.5 Effect on Energy Efficiency Ratio (EER)

The EER decreases with increase in the outdoor temperature. Figure 15 illustrates the percentage improvement or decrement in EER of all the tested RACs at different controlled conditions.

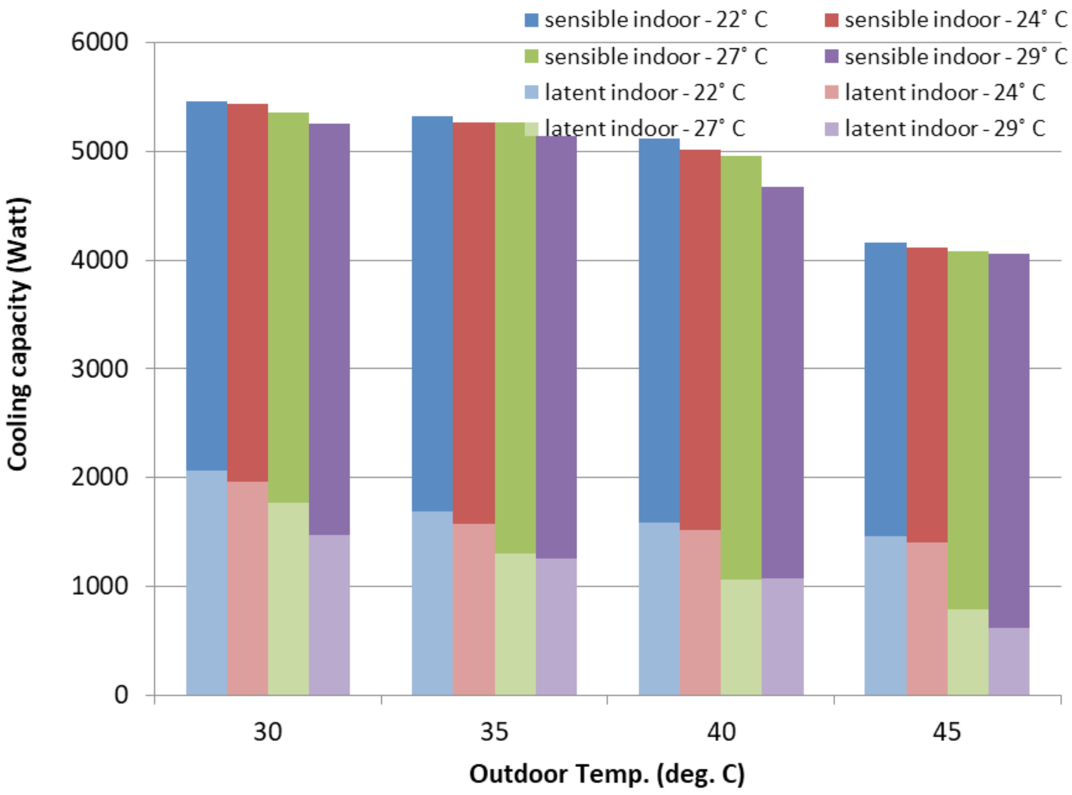
Figure 15: The percentage improvement or decrement in Energy Efficiency Ratio (EER) compared to rated conditions



9.7.6 Effect on Sensible to Latent Cooling Capacity Ratio

The breakup of total cooling capacity, in terms sensible and latent components, for varying indoor set-point at different outdoor conditions is captured in Figure 16.

Figure 16: Sensible and latent components of the total cooling capacity



Below is a sample test calculation sheet, calculating above parameters is as follows:

Table 33: Test report – Psychrometric chamber

TEST REPORT - Psychrometric chamber

Model	JTKM50SRV16	Date/Start Time	12-8-17 8:30	Test Name	IS 1391	Cooling Capacity Test	
Make	Daikin	Date/End Time	12-8-17 9:00	Temperature Conditions		Voltage/ Freq	Duration
Unit Sr. No.	0	File Name		Indoor (dbt/wbt)°C	22/16	230	0:30:00
Type of Unit	Inverter (50%)	Observer		Outdoor (dbt/wbt)°C	35/24	50	
Capillary (Id x length x Qty)	- - -	Gas qty (Grams)	-	Compressor Make		-	
Test Purpose	-	Remarks		Compressor Model		-	

Measurement Data	1	2	3	4	5	6	7	Average
Indoor Room Measurement Data								
Entering Dry Bulb Temp.(°C)	22.00	22.00	21.99	22.00	22.00	22.00	21.98	22.00
Entering Wet Bulb Temp.(°C)	16.12	16.12	16.10	16.10	16.10	16.10	16.10	16.11
Air Entering Relative Humidity (%)	59.93	59.93	59.84	59.79	59.80	59.80	59.93	59.86
Test unit Measurement Data								
Leaving Dry Bulb Temp.(°C)	14.10	13.99	14.00	14.10	14.10	14.00	14.10	14.06
Leaving Wet Bulb Temp.(°C)	13.10	13.10	13.00	13.00	13.00	13.00	13.10	13.04
Entering Air Enthalpy,H1(KJ/Kg)	47.22	47.22	47.16	47.16	47.17	47.17	47.17	47.18
Leaving Air Enthalpy,H2(KJ/Kg)	38.64	38.64	38.37	38.37	38.37	38.37	38.64	38.48
Enthalpy Dif. (KJ/Kg)	8.59	8.58	8.79	8.80	8.80	8.80	8.53	8.70
Sp. Volume of Air Leaving (m^3/Kg)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Out Door Room Measurement Data								
Entering Dry Bulb Temp.(°C)	35.10	35.10	35.12	35.11	35.11	35.10	35.11	35.11
Entering Wet Bulb Temp.(°C)	23.98	24.00	23.99	24.00	24.00	23.99	23.98	23.99
Air Entering Relative Humidity (%)	43.83	43.92	43.81	43.90	43.90	43.89	43.82	43.87
Suction Pressure (PSIG)								0.00
Discharge Pressure (PSIG)								0.00
Air Flow Measurement Data								
Barometric Pressure (Pa)	94390.00	94390.00	94390.00	94380.00	94370.00	94370.00	94360.00	94378.57
Static Pressure before nozzle (Pa)	104.70	108.60	105.60	103.00	108.90	110.00	106.00	106.69
Diff pressure across the nozzle (Pa)	253.80	255.90	255.60	249.50	247.89	241.63	242.30	249.52
Nozzle Dry Bulb Temp. (°C)	16.60	16.73	16.72	16.80	16.70	16.65	16.73	16.70
Air Flow (CMH)	771.32	774.06	773.61	764.49	762.21	752.34	753.58	764.52
Tested Data								
Tested Capacity (watt)	2112.87	2122.33	2173.40	2147.27	2139.93	2112.84	2050.32	2122.71
Tested Capacity (Btu/Hr)	7209.12	7241.40	7415.66	7326.48	7301.45	7209.00	6995.67	7242.68
% Rated Capacity (%)	42.26	42.45	43.47	42.95	42.80	42.26	41.01	42.45
Tested Sensible Capacity (watt)	1953.40	1986.77	1980.78	1934.62	1929.44	1928.88	1902.20	1945.16
Tested Latent Capacity (watt)	159.47	135.56	192.62	212.65	210.49	183.96	148.11	177.55
Sensible to Total Ratio (%)	92.45	93.61	91.14	90.10	90.16	91.29	92.78	91.65
Dehumidification capacity (Ltr/Hr)	0.17	0.14	0.22	0.25	0.24	0.21	0.16	0.20
Tested EER (Btu/Hr/Watt)	12.86	12.28	12.33	12.51	12.13	12.63	11.97	12.39
Tested EER (Watt/Watt)	3.77	3.60	3.61	3.67	3.55	3.70	3.51	3.63
Electrical Measurement Data								
Voltage (V)	229.10	229.13	229.43	229.12	229.00	229.34	229.26	229.20
Power (Watts)	560.53	589.60	601.32	585.60	602.00	571.00	584.30	584.91
Current (A)	2.44	2.47	2.52	2.48	2.54	2.47	2.49	2.49
Power Factor	0.78	0.78	0.77	0.78	0.77	0.77	0.77	0.77
Line Frequency (Hz)	50.10	50.10	50.00	50.10	50.20	50.10	50.00	50.09
Barometer Corrected Data								
Barometer Corrected Air Flow(CMH)	718.38	720.94	720.52	711.94	709.75	700.56	701.64	711.96
Barometer Corrected Capacity (Watts)	2146.36	2155.97	2207.86	2181.35	2173.95	2146.43	2082.96	2156.41
Barometer Corrected Capacity (Btu/Hr)	7323.39	7356.18	7533.21	7442.78	7417.53	7323.61	7107.05	7357.68
Barometer Corrected EER (Btu/Hr/Watt	13.07	12.48	12.53	12.71	12.32	12.83	12.16	12.58
Barometer Corrected EER (Watts/Watts	3.83	3.66	3.67	3.72	3.61	3.76	3.56	3.69

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