Prescriptive Approach for Achieving Energy Efficiency in India's Upcoming Affordable Housing

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ABSTRACT

The Pradhan Mantri Awas Yojana (PMAY), a flagship program of the Government of India, aims to provide affordable housing to the low-income communities. Fund allocation for each housing project is not possible for exclusive studies on energy-efficiency measures and thermal comfort (otherwise considered a 'luxury' by affordable housing residents). Hence this paper puts forth a simplified and prescriptive set of recommendations that are categorized based on climatic conditions. Literature reviews aided in initial inputs, which were further discussed for their feasibility of implementation during expert consultations. Building energy professionals, architects, and developers with significant knowledge on building science working on a range of projects and policies across India were consulted one-on-one. The responses were analyzed under three categories: (1) priority grouping of passive cooling strategies, (2) priority ranking of low energy cooling technologies, and (3) recommended building envelope materials. Final recommendations were laid out using a multi-criteria assessment considering the impact on other parameters such as cost, time and ease of application of the suggested interventions. It was found that Orientation, WWR and Window Shading were the high-impact, least cost-intensive strategies for hot & dry and composite climate; Orientation, Ventilation and the Use of ventilators for warm-humid climate and Orientation, Window Shading and Ventilation for temperate climate. Super-efficient fans like the BLDC were also recommended for all climatic conditions. Among building envelope materials, AAC blocks and hollow bricks were the most recommended wall materials; lime concrete and mud-phuska were recommended for roofs and EPS, fiberglass and mineral wool for insulation.

Introduction

Affordable housing is a crucial sub-sector of housing in India. Aligning with the vision to provide Housing for All, the Pradhan Mantri Awas Yojna (PMAY) was launched as a flagship program of the Government of India that aims to provide affordable housing to the vulnerable and under-privileged sector of the society. Households that fall in the annual income range of 0-3 Lakh are categorized as Economic Weaker Section (EWS) and 3-6 Lakh are categorized as Low-Income Group (LIG). Since the affordable houses are to be built at a rapid pace and least cost, there is a deficit of time and resources to be spent on detailed energy analysis and efficient building design leading to in-efficient and thermally uncomfortable construction of spaces. In this regard, the Eco-Niwas Samhita i.e., ENS (Bureau of Energy Efficiency 2018) which is the residential building energy code of India could be adopted and eventually enforced. However, faster adoption of ENS would require complimentary guidelines and simplistic handbooks for the end users to directly incorporate the recommendations that ensures ENS compliance and also makes buildings energy-efficient and thermally comfortable. Thus, this research included collecting, compiling, and analysing information through secondary desk research to derive best practices that shall be adopted. Due to the outbreak of COVID-19, site-visits were not suitable and thus, the findings from literature review were corroborated with experts during one-on-one structured stakeholder consultations.

Background

As of the 2011 Census, 377 million people reside in urban areas, representing 31% of the country's total population, with an expected increase of over 200 million by 2031 (Planning Commission 2013). As a part of the 12th Five Year Plan 2012-17, the Government of India appointed a Technical Action Group (TAG) to assess the demand-supply gap in the housing stock in Indian cities. Out of the total shortage of 18.78 million units in 2012, the housing shortage distribution across various income categories is 56% EWS, 40% LIG and 4% MIG and above (MoHUPA 2012). The 'Housing for all' initiative by the PMAY was thus implemented in three phases- (1) Phase I- April 2015 to March 2017 covered 100 selected cities in states/union territories (UTs) as per their willingness. (2) Phase II- April 2017 to March 2019 covered 200 additional cities (3) Phase III- April 2019 to March 2022 aims to cover all remaining cities (MoHUPA 2015). India is now in Phase III of the mission. The affordable housing PMAY-U status as of June 2021 is- (i) 11.29 million houses sanctioned (ii) 8.32 million houses grounded (iii) 5 million houses completed.

The affordable housing narrative is currently driven by the link between income and built space provisions and the cost of the dwelling unit as the determining criteria. There is limited or no focus on qualitative aspects that determine housing livability, basic thermal comfort and occupant productivity. To address this shortcoming, there are various ongoing policies and programs specific to the affordable housing scenario like the Rajiv Awas Yojna (RAY), National Urban Rental Housing Policy (NURHP), Smart Cities Mission and Atal Mission for Rejuvenation and Urban Transformation (AMRUT) (Herda, et al. 2017). This study also has a similar intent with an additional motive of working towards code adoption.

Significance of Study

Code adoption and enforcement is a challenging implementation issue worldwide. For affordable housing, the government has oversight of the project progress and project teams. This increases the scope of implementation compared to privately-owned residences. Compliance of building energy code in the affordable housing sector where a large proportion is likely to be self-built housing is challenging. Due to high project volumes and atypical perception on building energy-efficiency, fund allocation for exclusive studies on energy efficiency measures for each housing project will not be possible. Hence, a fundamentally prescriptive set of recommendations in line with a national standard or code like the Eco Niwas Samhita is needed. This is a strategy to improve code adoption in the residential sector with affordable housing being the point of initiation. The adoption and gradual enforcement here is an indirect approach as a byproduct of adopting the recommendation proposed in this paper. Figure-1 shows how this study is positioned at the macro level.

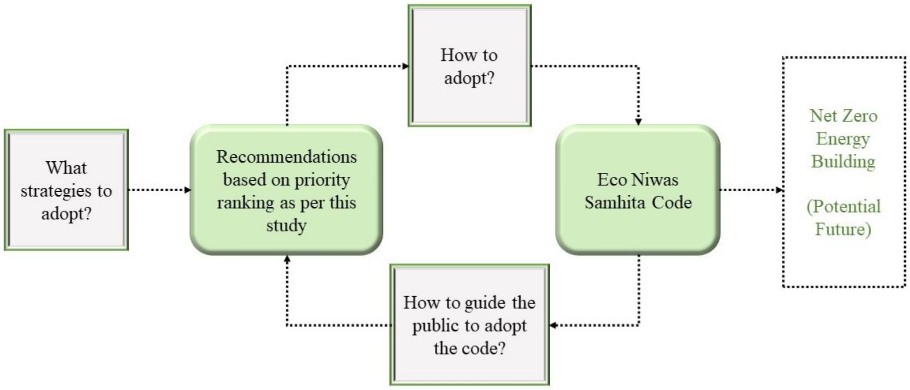

Figure 1. Positioning of the study at the macro level

It is important to understand and spread awareness about the strategies that can lead to stage-wise implementation. There are numerous strategies and, hence, reviewing existing literature helped in selecting a list of strategies based on their impact on building energy, thermal comfort, cost implication, and feasibility. The upcoming section discusses relevant literature reviews.

Literature Review

This section looks at the passive and low-energy cooling strategies that can potentially be incorporated into affordable housing projects across India. However, the applicability of these strategies depends on factors, such as climatic conditions, sun path and orientation, wind direction & temperature, ground temperatures and sky/cloud cover. Although the abovementioned factors need to be studied cautiously on a case-by-case basis, design recommendations can be standardized to a certain extent based on climatic conditions as per the following- passive and low energy cooling strategies. (Givoni 2008; IEA Annex 28 2001; Lechner 2021).

Passive Cooling Strategies

Passive cooling strategies are design interventions applied to buildings to control heat ingress, reducing cooling loads without increasing energy costs. These strategies are categorized based on the mode of cooling as follows: (1) Heat transfer through radiation (2) Heat transfer through conduction (3) Heat transfer through convection (Panchabikesan, Vellaisamy and Ramalingam 2017). The following subsections briefly discuss the strategies for tackling the different heat transfer modes. This study has incorporated thresholds from the ENS wherever possible and necessary when providing questionnaires to the expert stakeholders. Tables 1, 2 and 3 puts forth best practices from literature reviews and applicable thresholds from ENS for heat transfer through radiation, conduction and convection respectively (BEE 2018).

Heat transfer through radiation.

Radiation is the transfer of heat in the form of infrared rays and electromagnetic waves. Three of the most high-impact strategies—building orientation, optimizing the façade’s Window-to-Wall-Ratio (WWR), and designing shading devices are dependent on the radiation component of heat. ***(i) Orientation**:* A crucial initial design decision is orienting the longer axis of a building based on solar path, altitude angles, azimuth angles, cloud cover, global horizontal radiation, prevailing wind direction, and temperature of incoming wind. ***(ii) Window-to-wall ratio (WWR):*** The window area with respect to the area of the façade on which it rests is termed the window-to-wall ratio. Window here indicates the entire opening, including glazing and the outer frame. ***(iii) Window shading**:* Providing shading devices, either horizontal or vertical, to shade some or all parts of a window during various months/seasons/throughout the year is called window shading

Table 1. Best practices from literature reviews and applicable thresholds from ENS- Radiation

Orientation	WWR	Window shading
- For passive cooling, orient the building along the N-S axis. - Additionally, the design needs to ensure that the floor plates are thin and not too deep for increasing the impact of passive cooling and enhancing daylight penetration. It is also important to incorporate natural ventilation. - It is to be noted that ENS 2018 recommends calculating orientation factor which is a measure of the amount of direct and diffused solar radiation that is received on the vertical surface in a specific orientation. (Elghamry and Azmy 2017; Pai and Siddhartha 2015; Deshmukh and Kherde 2013).	- East and west façade - minimum WWR (20-30%) - South façade - <30% WWR - North façade - high WWR is acceptable due to low exposure to direct solar radiation. - Assembling should be cautiously done to avoid thermal bridging from the exterior portion to the interior. - Apart from this, to optimize heat and daylight, the ENS 2018 recommends the following minimum visible light transmittance (VLT) for various WWR: 0.27 VLT for 0-30% WWR; 0.20 for 31-40%; 0.16 for 41-50%; 0.13 for 51-60% and 0.11 for 61-70% (Pathirana, Rodrigo and Halwatura 2019; Didwania, Garg and Mathur 2011; Izadyar et al. 2019).	- South façade - horizontal overhangs - East and west façades - horizontal + vertical fins (preferred) - North façade – horizontal overhangs (if needed for resistance to rain and weatherproofing) - Designing and implementing only static shading devices is not sufficient to shade the window throughout the year. A combination of static and operable shading can effectively reduce heat gains. This may be more feasible in residential buildings than affordable housing projects. (Szokolay 2004; Jaboyedoff et al. 2017).

Heat transfer through conduction.

The transfer of heat through contact with another material is called conduction. Strategies focused on wall assemblies, roof assemblies, glazing materials, and assemblies for the building are termed ‘envelope strategies.’ This subsection breaks down the abovementioned envelope components and highlights best practices and their applicability to affordable housing. ***(i) Wall assembly and properties*****:** The specifications and properties of the wall materials that constitute the assembly govern the effectiveness of heat conduction through the wall. The thermal properties of individual wall materials like the conductivity, specific density, specific heat, and thickness assist in calculating the assembly’s conductance. ***(ii) Window glazing assembly and properties*****:** ‘Window glazing’ here refers to the glass pane/panes that constitute the window. The performance metrics governing these glazing units include the solar heat gain coefficient (SHGC), glazing type, U-value, and VLT. Windows and glazing are the thermally weakest areas in a building envelope. Therefore, effective and correct decision-making regarding these components is vital. ***(iii) Roof assembly and properties:*** Hardscapes in a roof contribute to high heat gain, which is eventually conducted through the roof assembly. The performance metrics here include the U-value, surface reflectance, emissivity, and solar reflectance index (SRI). Roofing materials with high SRI values are termed ‘cool roofs.’ There are many efficient roofing methods, such as vegetated roofs, concrete roofs, insulated roofs, roof gardens, solar photovoltaic roofs, bisolar roofs, double-skin roofs, and roof ponds

Table 2. Best practices from literature reviews and applicable thresholds from ENS-Conduction.

Wall assembly & properties	Glazing assembly & properties	Roof assembly & properties
- Materials, material assemblies and their availability in various locations must be determined, and insulation must be selected accordingly. - It is essential to use insulation that does not use HCFCs as foam blowing agents. - ENS recommends that for all climatic conditions (Hot & dry, warm- humid, composite and temperate) except cold, U-value = 0.55 W/m2K (AEEE 2018; BEE 2017).	-The WWR should ideally be determined before selecting the glazing and glazing parameters. -Oversizing or undersizing of windows based on building orientation and daylight requirements may lead to unintended heat exchange. Thus, optimization is essential. -ENS recommends that for all climatic conditions (Hot & dry, warm- humid, composite and temperate) except cold, U-value = 3 W/m2K Max SHGC: 0.27 (east, west, south) Max SHGC: 0.5 (north - for latitudes ≥15) Max SHGC: 0.27 (north - for latitudes <15) (BEE 2017; Keeler and Vaidya 2016; Kumar and TP Babu 2016).	- Selection of materials and assembly for roofs can be made in conjuncture with that of walls. - ‘Cool roofs’ are recommended for existing buildings as one of the most feasible low-cost energy reduction strategies. - ENS recommends that for all climatic conditions (Hot & dry, warm- humid, composite and temperate) except cold, U-value = 0.33 W/m2K (Abuseif and Gou 2018).

Residential envelope transmittance value (RETV): The RETV is the net heat gain rate through the building envelope, excluding the roof. RETV is not a strategy, but rather an approach to calculate the heat gains resulting from all of the abovementioned building components. The ENS 2018 discusses RETV and its formula and approach to calculation. Limiting the RETV value to 15W.sqm (excluding roof) reduces heat gains from the envelope (BEE 2018).

Heat transfer through convection.

Convection is the transfer of heat through the movement of air. The air movement through natural means into and outside the building is termed ‘natural ventilation’. There are various natural ventilation techniques. However, considering the various complexities and implementation logistics concerning affordable housing, the scope in this paper is limited to cross and night-flush ventilation. ***(i) Natural cross-ventilation:*** The movement and cross-flow of air between two sides of a building is called ‘cross ventilation’. The Air Changes per Hour (ACH) keeps varying in this natural cooling mode based on micro-atmospheric conditions. The challenge here is that the airflow rate can be high in certain places and low in other places, leading to imbalance and asymmetrical cooling demand. ***(ii) Night flush ventilation:*** The practice of free cooling or cooling at night by opening the windows and letting in cooler ambient air from the outside is called ‘night flush ventilation.’ This cools the mass of the building and prepares it for the following day, when it acts as a heat sink. Integrating other strategies like shading and optimized orientation enhances the effect of night flush ventilation demand

Table 3. Best practices from literature reviews and applicable thresholds from ENS- Convection.

Cross and Night flush ventilation (both)	ENS recommendation
- The wind direction needs to be analyzed, and the ventilation strategy optimized accordingly based on orientation and natural ventilation mechanisms to receive fresh air - The air temperature also needs to be studied before cross ventilation or opening sizes are selected, as, otherwise, this can be counterproductive. - ACH largely depends on the size of the window and velocity of air passing through it. Hence, the sizes of the windows with respect to the floor area or the WFR needs to be calculated/set accordingly (IEA Annex 28 2001; Izadyar et al. 2019; Jaboyedoff et al. 2017; AEEE 2017).	ENS recommends the following for various climatic conditions: - Minimum WFR for composite climate to be 12.5%; warm-humid climate to be 16.6%; hot & dry climate to be 10% and temperate to be 12.5%. - Fewer deep floor plates, in order for night flush ventilation to be effective, are recommended in general.

Low-Energy Cooling Strategies

In addition to the identified design alternatives, several alternative low-energy cooling strategies have also been identified. These are power-based equipment that provide cooling and thermal comfort. These technologies usually use a heat sink and an energy-consuming component such as a fan, blower, pump, or a combination of these (IEA Annex 28 2001). There are numerous low-energy cooling strategies. However, this study selected three strategies based on applicability, affordability, scalability, and market potential.

Super-efficient fans.

A majority of households—almost 93% of Indian families—use ceiling fans to achieve thermal comfort. Many new technologies that reduce energy consumption by over 40-50% from conventional appliances have emerged recently, such as brushless direct current (BLDC) fans. These fans are super-efficient and can provide ventilation and air with significantly less energy consumption, i.e. 28-30 watts (W), compared to the ~50-70 W consumed by an average fan. BLDC fans are ~63% more energy-efficient than conventional non-star-rated ceiling fans and consume 36% less energy than a 5-star rated fan with an alternating current (AC) induction motor making them a good choice for affordable housing projects (AEEE and ACEEE 2019). However, their capital cost is almost twice that of a conventional fan, and the payback period is less than two years in most cases. A BLDC fan motor is also lighter and less noisy than a conventional fan motor (PC, et al. 2015).

Evaporative coolers.

Evaporative air coolers are commonly known as desert or swamp coolers and have applications in residential and commercial settings. They work on the simple principle of evaporation and the use of water as a refrigerant. They work well in India’s two major climatic zones, i.e. hot-dry and composite; however, their performance decreases in areas with high relative humidity. There are three basic types of evaporative air coolers- In Direct Evaporative Air Coolers (DECs), cooling pads are used as the heatsink and add humidity to the air, resulting in cooling. In Indirect evaporative air Coolers (IECs), a heat exchanger is used as the cooling medium. In this technology, no humidity is added to the air supply. This makes it better suitable than DECs for non-residential sectors and thus can apply to almost all climates depending on the ambient climatic condition. In Indirect- Direct Evaporative air Coolers (IDECs), also known as two-stage evaporative air coolers, the IEC technology is used in the first stage with a DEC in the second stage. It is the most efficient technology of the three. Humidity is added to the supply air, but less is required than in DECs (Amer, Boukhanouf and Ibrahim 2015; Panchabikesan, Vellaisamy and Ramalingam 2017). Water availability in the locality is a crucial decision-making criterion as evaporative cooling requires water as the cooling medium. DECs work best in areas that require high sensible cooling and high humidification. IECs work best in areas that require high sensible cooling without addition of humidity. IDECs work best in areas that require high sensible cooling and less humidification (NREL 2014).

Methodology

The study's methodology is depicted in Figure 2. The study included collecting, compiling, and analyzing information through secondary research. This study considers two performance parameters: cooling load reduction potential (for the benefit of residents) and cost impact (for the benefit of developers) to achieve a mutually beneficial solution. Literature reviews enabled a direction towards arriving at initial recommendations (as shown in table-4) to initiate questions/ conversations with expert stakeholders by linking these theoretical/ research-oriented numbers with on-ground reality and their field experience. The study required inputs from multiple sectoral experts with 15-20+ years of experience in the building energy field specific to India. A total of five practicing architects and green building consultants, two developers, two policymakers at the central level, and one academician were consulted. These are experts selected from the committee lists who played key roles in the development of various building energy codes and green rating systems in India. Architects and green building consultants could provide input on appropriate design guidance and challenges in incorporating various strategies proposed; developers could add value on affordability and feasibility; policymakers could provide input on potential macro-level impacts and challenges in adhering to codes and standards; and academicians could provide input on bridging theoretical knowledge with on-the-ground reality.

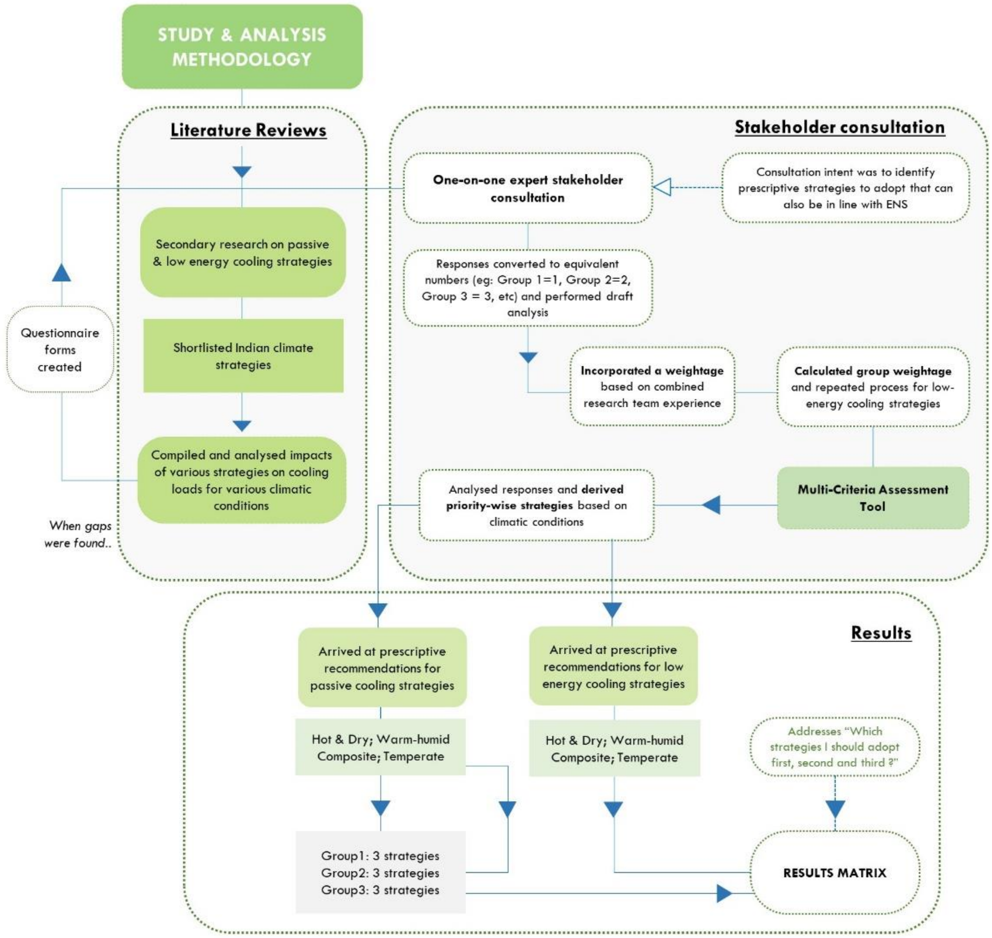

Figure 2 Study methodology

Passive strategies for each type of climate were grouped based on their impacts on cooling load, comfort, and associated costs by categorizing them as Group-1: Highly recommended/ Lowest cost; Group-2: Medium recommended / Medium cost and Group 3: Less recommended/ Highest cost. Low energy cooling strategies were categorized as Rank1: Highly recommended and Rank-2- Medium recommended strategies. The responses were collated and converted to equivalent numbers to enable quantitative response-oriented research analysis. These numbers were then normalized using a group weighted average calculation. Weightages for Groups 1, 2, and 3 were assigned as 50%, 30%, and 20% and normalized to a group weightage of 200 using a multicriteria approach.

These studies were done for all climates except cold climate as India is predominantly a tropical country and is cooling-dominated. Groups 1, 2, and 3 cover nine strategies; however, the individual strategies are not ranked from 1 to 9. While Groups 2 & 3 should not be neglected, the grouping has been done to encourage investors to start with Group 1 strategies as a first step and gradually consider Group 2 and Group 3 strategies.

Limitations Of The Study

The study scope was limited to developing a broad set of recommendations to help facilitate stakeholders at Urban Local Bodies (ULBs) to incorporate passive and low energy features in their tender documents, technical documents, specification and schedule of rates. Since building physics is a broad spectrum, and multiple variables are involved in decision-making, the study inherently involves several assumptions and neglects certain variables that need to be studied on a case-by-case basis. Cold climatic conditions are not part of the study as India is primarily a cooling-dominated tropical country. The study's methodology and the associated recommendations may not work in all contexts but it will still lead to better building design and energy reduction in most cases by making these recommendations widely and publicly available and accessible. Strategies are grouped and not ranked as individual context varies. This study does not include numerical quantification through building energy simulations.

Analysis and Findings

Literature reviews enabled in providing initial recommendations as shown in Table-4. These were then taken forward to expert stakeholders as explained in the methodology section.

Table 4 Literature-based initial recommendations on passive strategies

Sl.no	Passive strategies	General Recommendation under passive strategy based on literature reviews
1	Orientation	N-S predominantly- option 1; NW-SE- option 2
2	WWR	<30%
3	Window Shading	South- horizontal; East & west- vertical; North- optional
4	Glazing type	Single glazing - E, W, N; Double glazing- south only
5	Ventilation- cross and night flush (V-CN)	Openings on 2 sides of room with WWR<30% each with min. WFR
6	Ventilators (V)	2' high ventilators above 7' in habitable areas
7	Wall materials/ Techniques (Walls)	Solid burnt clay bricks; Hollow & Fly ash bricks; Solid concrete block; AAC block; CSEB; RCC; Lime concrete; Cellular concrete
8	Envelope insulation (Insulation)	Below are commonly available materials in India without HCFCs: Fiberglass; mineral wool; Cellulose
9	Roof materials & techniques (Roofs)	Below are commonly available materials in India as per ENS: Brick tile; Lime concrete; Mud Phuska; AC sheet
Low energy cooling technologies		
1	BLDC fans	Can be installed for all climatic conditions- Hot and dry, warm-humid, composite, and temperate
2	Evaporative cooling	More suitable for hot-dry and composite climates. DECs can be used for hot-dry and composite climates. IECs can be used for warm-humid and composite climates.

The collated responses were analyzed, and conclusions were drawn for the following- (1) Passive cooling strategies (2) Low-energy cooling strategies (3) Building envelope materials

I. Recommendations- Passive Strategies

The passive strategies considered were covered in the one-on-one consultations, and results were obtained for each climate when the cooling load and cost were optimized. This section analyses the results based on various climatic conditions as depicted through figures 3 to 6. The bars indicate the experts' response percentage for impact of each strategy on reducing cooling load, as labeled in the primary y-axis, and the circles indicate the experts' response percentage based on the lowest incremental cost as labeled in the secondary y-axis. Higher the bar on primary y-axis indicates higher effectiveness of the corresponding strategy in reducing cooling load. Higher the circle on secondary y-axis indicates the best cost-effectiveness of the corresponding strategy.

Hot & dry climate. For hot & dry climates, stakeholder consultation findings indicate that orientation, WWR, and window shading are the highest-impact strategies (Group 1) considering cooling load reduction potential, cost implication, and feasibility of implementation in affordable housing. The medium-impact strategies (Group 2) include cross & night flush ventilation, design of ventilators, and roof assembly strategies. The lowest-impact strategies (Group 3) are glazing assembly, envelope insulation, and wall materials/ techniques. The results are depicted in the graph in Figure 3.

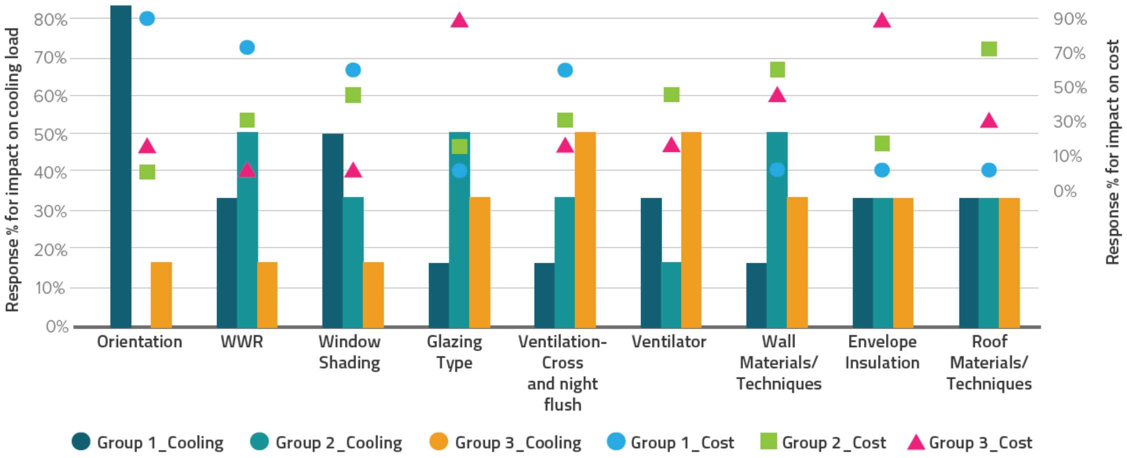

Figure 3. Hot & dry climate- Response % for impact on cooling load vs. cost for priority groups

For example, it can be observed from the graph that for hot and dry climate, 83% of the experts selected 'orientation' to be a Group-1 strategy based on cooling load. This is shown in the primary y-axis indicated by the first bar under 'orientation'. 86% also selected orientation as a Group-1 strategy based on cost implications. This is shown in the secondary y-axis indicated by the blue circle under orientation.

Warm-humid climate. For warm-humid climates, findings from stakeholder consultation indicate that orientation, cross & night flush ventilation, and design of ventilators are Group-1 strategies as depicted in Figure 4.

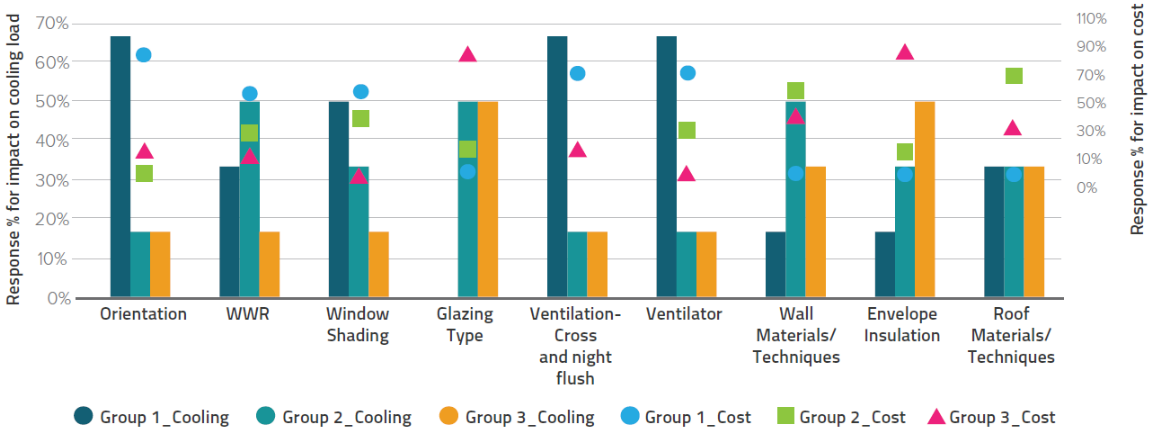

Figure 4. Warm-humid climate- Response % for impact on cooling load vs. cost for priority groups

Group 2 strategies include WWR, window shading and roof assembly. Group-3 strategies remain the same. For example, it can be observed from the graph that 67% of the experts selected orientation to be a Group-1 strategy based on cooling load and 86% selected it to be a Group-1 strategy based on cost implications as well.

Composite climate. For composite climatic conditions, stakeholder consultation findings indicate that priority group findings are similar to hot & dry climatic conditions. The results are depicted in the graph as shown in Figure 5.

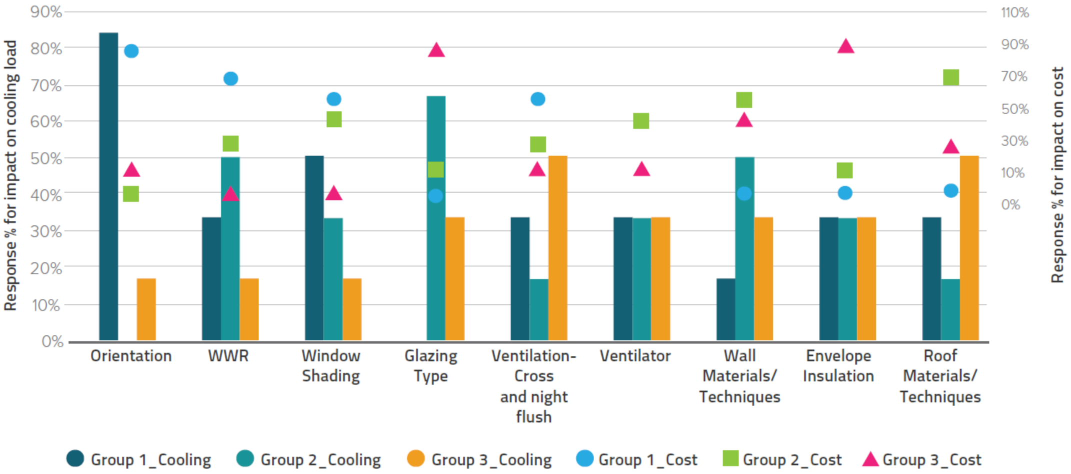

Figure 5. Composite climate- Response % for impact on cooling load vs. cost for priority groups

Temperate climate. For temperate climates, stakeholder consultation findings indicate that orientation, window shading, and cross & night flush ventilation are Group 1 strategies. Group 2 strategies are WWR, design of ventilators, and roof assembly strategies. Group-3 strategies remain the same. The results are depicted in the graph as shown in Figure 6. It can be observed from the graph that, 67% of the experts selected orientation to be a Group-1 strategy based on cooling load and 86% selected it to be a Group-1 strategy based on cost implication as well.

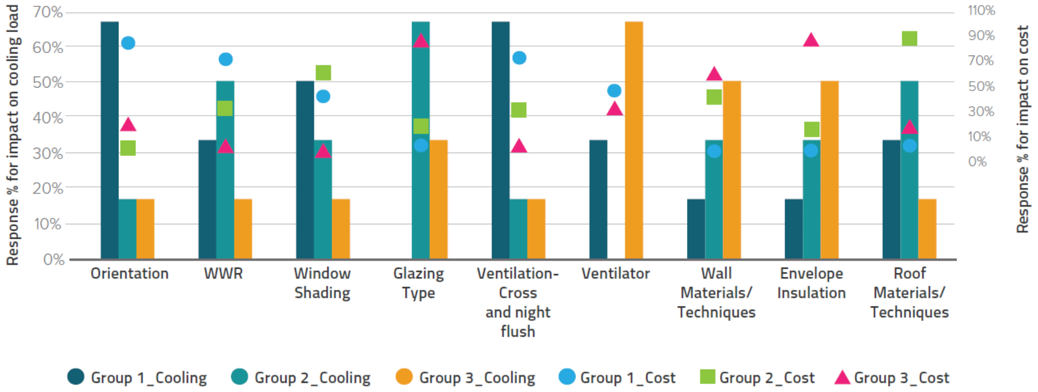

Figure 6. Temperate climate- Response % for impact on cooling load vs. cost for priority groups

As per the findings, nine strategies were categorized into three groups of three strategies each for each type of climate as shown in Table 5.

Table 5. Summary of findings- passive cooling strategies

Climate	Hot & dry	Warm-humid	Composite	Temperate
Group 1	Orientation	Orientation	Orientation	Orientation
	WWR	V-CN	WWR	Window Shading
	Window shading	Ventilators	Window shading	V-CN
Group 2	Ventilators	WWR	Ventilators	WWR
	V-CN	Window Shading	V-CN	Ventilators
	Roofs	Roofs	Roofs	Roofs
Group 3	Walls	Walls	Walls	Walls
	Glazing type	Glazing type	Glazing type	Glazing type
	Insulation	Insulation	Insulation	Insulation

From the cooling load reduction potential and cost perspective, orientation, WWR, and window shading are in Group 1 for the hot & dry and composite climates. For temperate climates, WWR is replaced by 'ventilation - cross and night flush' in Group 1. For warm-humid climates, orientation, cross & night flush ventilation and ventilators are in Group 1. Roof materials & techniques are in Group 2 for all climates. Similarly, glazing, envelope insulation and wall materials & techniques are in Group 3 for all climates. There are mild variations in the distribution of the remaining strategies across all climates and groups optimized with cost findings mainly due to differing ambient climatic conditions. Weightages were assigned as explained in the methodology section.

II. Recommendations- Low- Energy Cooling Strategies

The low-energy cooling strategies considered have been ranked as Rank-1 and 2 instead of groups. Given their lower overall feasibility in affordable housing projects as they are more expensive than passive strategies, they are less in number, and hence ranking is more relevant than grouping. It can be seen from Table 6 that super-efficient fans are the most recommended Rank 1 strategy across all climates, followed by evaporative cooling systems. DECs are recommended for all climates except warm-humid climate, where IECs are preferred due to their ability to function well in high ambient relative humidity. Radiant cooling through floors was originally ranked third among the strategies. However, experts expressed concern over the installation and usage of this technology, given its feasibility in affordable housing and its relatively high initial and O&M costs.

Table 6. Summary of findings- low energy cooling strategies

Climate	Rank 1 recommendations (high-impact)	Rank 2 recommendations (medium-impact)
Hot & dry; Composite; Temperate	Super-efficient fans	Direct evaporative cooling
Warm-humid	Super-efficient fans	Indirect evaporative cooling

III. Recommendations- Building Envelope Materials

The priority grouping of passive strategies and ranking of low-energy cooling strategies have been discussed in detail in the previous sections. However, while conducting expert stakeholder consultations, additional recommendations on the usage of envelope components were added to the analysis matrix and are summarized in Table 7 in non-ranked order.

Table 7. Summary of findings- Building envelope materials

Building components		Hot & dry	Warm-humid	Composite	Temperate
Wall materials	Exterior wall materials	AAC	AAC	AAC	AAC
		Hollow bricks	Hollow bricks	Hollow bricks	Hollow bricks
		Clay bricks	Clay bricks	Cellular concrete	Clay bricks
		Fly ash	Cellular concrete	Fly ash	Fly ash
Roof materials- all climates	Materials	Lime concrete, mud-phuska			
	Techniques/ treatment	Filler slab, brick tiles, SRI painting, China mosaic			
	Roof with insulation	RCC concrete roof with over deck insulation			
		Insulation with white tile or hollow cavity in construction in the absence of insulation			
Envelope	Insulation material	EPS, fiberglass, mineral wool			

insulation-all climates	Additional recommendations	1. Insulation decisions depend on cost 2. Insulation for roof more preferred than walls 3. Simple insulation will suffice for basic thermal comfort

For walls, experts recommended autoclaved aerated concrete (AAC) blocks and hollow bricks for all climates. Clay bricks are recommended for all climates except composite, whereas fly ash is recommended for all except warm-humid. For roofs, lime concrete and mud-phuska are recommended. For surface treatment, SRI painting, China mosaic tiles, and brick tiles are preferred. Filler slab as a roof technique is also widely accepted. Extruded polystyrene (XPS), expanded polystyrene (EPS), glass wool, mineral wool, and fiberglass are most widely recommended for envelope insulation. Experts recommend insulating the roof rather than the walls if insulation is allocated in the project. In the expert stakeholder consultations, responses did not vary much across various climates, as most experts stated that high-performing building materials perform consistently well across the different climates in the country, as India is largely a tropical country.

Conclusion

The Government of India already has numerous schemes to enable access to affordable housing for the EWS, LIG, and MIG groups. In addition to this, India needs programs focused on creating awareness and building capacities of various stakeholders such as ULBs, developers, and practitioners to incorporate thermal comfort and cost-optimized energy efficient strategies into affordable housing. Although each project needs to be studied cautiously on a case-by-case basis, design recommendations can be standardized to a certain extent based on climatic conditions. This study provides such recommendations and enables relevant stakeholders like investors, developers, and architects to take the first step towards sustainability, considering fundamentally enhanced cooling and low cost, and help in decision-making by selecting appropriate passive, low-energy cooling strategies and building materials. The following are the study’s key conclusions:

1. Orientation and window shading are the most recommended passive strategies across all climates except warm-humid, where ventilation is also recommended among Group 1. This is primarily attributed to the low cost involved in incorporating orientation as a strategy.
2. Group 3 strategies are the same across all climates: glazing, wall materials & techniques, and envelope insulation mainly due to the high cost involved with these strategies.
3. For low-energy cooling strategies, super-efficient fans like BLDC fans rank first, and evaporative cooling systems rank second. Super-efficient fans are unanimously ranked first because of their affordability and short payback period.
4. Concerning building envelope materials and construction, experts recommend AAC and hollow bricks for walls, lime concrete and mud-phuska for roofs, and EPS, fiberglass, and mineral wool for insulation. As most experts consider India ‘predominantly hot’, their responses on building material selection were mostly similar.

Way forward

Achieving thermal comfort in most Indian climatic conditions in a BAU scenario requires mechanical ventilation such as evaporative cooling or air conditioning. However, affordable housing occupants in India have low purchasing power for products like air conditioners and coolers. Thus, thermal comfort in affordable housing needs to be prioritized, along with energy efficiency. To understand and contextualize the need to reduce cooling load and energy consumption, the housing shortage and projected housing stock need to be studied. Therefore, the following are identified as potential topics for future research and development-

(1) Quantification of passive strategies' cooling load reduction and cost through building energy simulations and cost analyses specific to the geographic area.
(2) Pilot implementation and hand-holding for developers to incorporate energy efficiency into affordable housing.
(3) Developing business models and financial instruments for creating and sustaining market for thermally comfortable and energy-efficient affordable housing.
(4) Developing eco-labelling of materials and its economic significance.
(5) Developing training and capacity building modules to cater to various stakeholder groups (ULBs, developers, building professionals and academicians).

References

Abuseif, Majed, and Zhonghua Gou. 2018. "A Review of Roofing Methods: Construction Features, Heat Reduction, Payback Period and Climatic Responsiveness." *Energies.* Gold Coast.

AEEE and ACEEE. 2019. "Mainstreaming Super Efficient Appliances in India."

AEEE. 2017. *Thermal Comfort For All- Sustainable and Smart Space Cooling.* New Delhi: Shakti Sustainable Energy Foundation.

Alliance for an Energy Efficient Economy. 2018. *Mainstreaming thermal comfort for all and resource efficiency in affordable housing, Status review of PMAY-U mission to understand barriers and drivers.* New Delhi: Shakti Sustainable Energy Foundation.

Amer, O, R Boukhanouf, and HG Ibrahim. 2015. "A Review of Evaporative Cooling Technologies." *IJESD.*

Bureau of Energy Efficiency, Ministry of Power. 2018. *Eco- Niwas Samhita, Energy Conservation Building Code for Residential Buildings: Part-1 Building Envelope.* Code, New Delhi: Government of India.

Bureau of Energy Efficiency, Ministry of Power. 2017. *Energy Conservation Building Code (ECBC).* New Delhi: Government of India.

Commission, Planning. 2013. *Twelfth Five Year Plan (2012- 2017)- Faster, more inclusive and sustainable growth, Volume-1.* New Delhi: Government of India.

Deshmukh, Nikhil V, and Yogesh P Kherde. 2013. "Case Study on Building Orientation." *IJSR.*

Didwania, Srijan, Vishal Garg, and Jyotirmay Mathur. 2011. "Optimization of window-wall ratio for different building types." *ResearchGate.*

Elghamry, Rania, and Naveen Youssef Azmy. 2017. "Building Orientation and its impact on the energy consumption." *Research Gate.*

Givoni, Baruch. 2008. *Passive and Low Energy Cooling of Buildings.* Wiley.

Herda, Gregor, Sonia Rani, Prathiba, Ruth Caleb, Rajat Gupta, Megha Behal, Matt Gregg, and Srijani Hazra. 2017. *Sustainable social housing in India: definition, challenges and* *opportunities - Technical Report.* Oxford: Oxford Brookes University, Development Alternatives, The Energy and Resources Institute and UN-Habitat.

ICRA, and FICCI. 2020. *Affordable Housing.* New Delhi: ICRA; FICCI.

IEA Annex 28, Energy Conservation in Buildings and Community Systems Programme. 2001. *Technology selection and eary design guidance.* United Kingdom: Construction Research Communications Ltd.

Izadyar, Nima, Wendy Miller, Behzad Rismanchi, and Veronica Garcia-Hansen. 2019. "Impacts of facade openings' geometry on natural ventilation and occupants' perception: A review." *Building and Environment.*

Jaboyedoff, Pierre, Sameer Maithel, Ashok Lall, Saswati Chetia, Prashant Bhanware, and Bharat Reddy. 2017. "Energy Efficient Building Envelope & Ventilation Strategies For Multi-Storey Residential Buildings in India." *nternational Symposium to Promote Innovation & Research in Energy Efficiency 2017.* Jaipur.

Keeler, Marian, and Prasad Vaidya. 2016. *Fundamentals of Integrated Design for Sustainable Building.* San Francisco: Wiley.

Kumar, Kiran, Saboor S, and Ashok TP Babu. 2016. "Experimental and Theoretical Studies of Window Glazing Materials of Green Energy Building in Indian Climatic Zones." *International Conference on Recent Advancement in Air Conditioning and Refrigeration, RAAR.* Bhubaneshwar.

Lechner, Norbert. 2021. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects.* New York: Wiley.

MoHUPA. 2012. *Report of the Technical Group on Urban Housing Shortage (TG-12) (2012-2017).* New Delhi: Government of India.

MoHUPA, Ministry of Housing and Urban Poverty Alleviation. 2015. *Pradhan Mantri Awas Yojna (PMAY).* New Delhi: Government of India.

NREL. 2014. "Multistaged Indirect Evaporative Cooler Evaluation." Denver.

Ozone Cell, Ministry of Environment Forest & Climate Change (MoEF&CC). 2017. *HCFC Phase-out and Energy Efficiency in Buildings.* New Delhi: Government of India.

Ozone Cell, Ministry of Environment, Forest & Climate Change (MoEF&CC). 2019. *India Cooling Action Plan (ICAP).* New Delhi: Government of India.

Pai, Maya Yeshwanth, and Siddhartha. 2015. "Effect of Building Orientation and Window Glazing on the Energy Consumption of HVAC System of an Office Building for Different Climate Zones." *IJERT.*

Panchabikesan, Karthik , Kumaresan Vellaisamy, and Velraj Ramalingam. 2017. "Passive cooling potential in buildings under various climatic conditions in India." *Renewable and Sustainable Energy Reviews.* Chennai: Elsevier.

Pathirana, Shakila, Asanka Rodrigo, and Rangika Halwatura. 2019. "Effect of building shape, orientation, window to wall ratio and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate." *IJERT.*

PC, Sahid, Muhammed Shafi, Irshad PM, Vishnu P, and Albin Thomas. 2015. "Energy Efficient Ceiling Fan using BLDC Motor." *IJERT.* Kerala.

Szokolay, Steven V. 2004. *Introduction to Architectural Science- the basis of sustainable design.* Burlington: Architectural Press.