सत्यमेव जयते
Goverment Of India

PASSIVE & LOW ENERGY COOLING STRATEGIES FOR ACHIEVING THERMAL COMFORT IN INDIA'S UPCOMING AFFORDABLE HOUSING

SEPTEMBER 2022

OZONE CELL
MINISTRY OF ENVIRONMENT, FOREST & CLIMATE CHANGE
GOVERNMENT OF INDIA

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और
श्रम एवं रोज़गार
भारत सरकार

सत्यमेव जयते

MINISTER
ENVIRONMENT, FOREST AND CLIMATE CHANGE
AND
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GOVERNMENT OF INDIA

स्वच्छ भारत
एक कदम स्वच्छता की ओर

भूपेन्द्र यादव
BHUPENDER YADAV

आज़ादी का अमृत महोत्सव

MESSAGE

Understanding thermal comfort is important since it not only lays the foundation for building design, but also affects the field of sustainable design. The need to ensure thermal comfort for all and access to cooling across the populace is important for tropical countries like India. Thermal comfort depends on the air temperature, humidity, radiant temperature, air velocity, metabolic rates, and clothing levels.

Almost half of the energy used in our society is consumed by the building sector in design, construction, and operation and much of that energy is used to cool and/or to heat buildings. Air conditioning alone accounts for 44% of a building's energy consumption. Declining energy resources and an awakening environmental consciousness have created an interest in climate-responsive, energy conserving designs and innovative mechanical strategies that allow for more personal control of thermal comfort.

Adopting models of thermal comfort leads to increasing energy-efficiency in building design. Constructing residential buildings in smart ways results in the use of minimal resources to cool and heat the house as the seasons change and can significantly reduce energy costs. Some of these best practices include passive measures comprising using the sun's energy for heating and cooling living spaces, (the building itself, or some element of it,) taking advantage of the natural energy potential of materials and air that have been exposed to the sun.

The study of 'Passive and low energy cooling strategies for achieving Thermal Comfort in India's upcoming Affordable Housing' aims to disseminate best practices for architects, building professionals and end users to adopt energy-efficient strategies for constructing buildings and will help a long way in promoting passive cooling measures in building construction leading to thermal comfort.

I congratulate all team members for preparation of this Report.

With best wishes.

Date: 10 .09.2022

(Bhupender Yadav)

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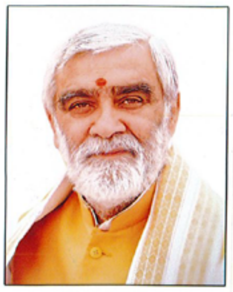

सत्यमेव जयते

आहारशुद्धौ सत्त्वशुद्धिः

एक कदम स्वच्छता की ओर

राज्य मंत्री
पर्यावरण, वन एवं जलवायु परिवर्तन
उपभोक्ता मामले, खाद्य और सार्वजनिक वितरण
भारत सरकार
MINISTER OF STATE
ENVIRONMENT, FOREST AND CLIMATE CHANGE
CONSUMER AFFAIRS, FOOD & PUBLIC DISTRIBUTION
GOVERNMENT OF INDIA

MESSAGE

Passive cooling includes a wide range of specific solutions aimed at avoiding direct solar heat accumulation, storing fresh air within the building envelope, removing gained heat, and slowing heat transfer from the external environment into the building. Thick or well-insulated walls, proper openings, screening systems, and outdoor spaces offering shade and natural ventilation are some of the possible solutions to increase thermal comfort and at the same time to save energy. Facades and roofs, as elements most exposed to solar radiation, offer important heat exchange surfaces. Their design can help to reduce overheating in the building, without energy waste. Using green roofs and facades, painting roofs with reflecting colours or using roof tile vents are among the most used solutions.

Maintaining thermal comfort for building occupants is one of the most important goals of architects and design engineers. If we can understand the variables of thermal comfort in our regional climatic contexts, and the mechanisms by which they operate in relation to human physiology, then we can design buildings that provide comfort in more rich and economical ways than a standard heating, ventilation and air-conditioning solution.

The Study on Passive & Low Energy Cooling Strategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing has been brought out at a very appropriate time considering that affordable housing for all is a priority area.

The publication would serve as an important resource material and should be disseminated widely amongst all concerned stakeholders. In addition, efforts should also be made to adopt the proposed recommendations by the concerned agencies.

(ASHWINI KUMAR CHOUBEY)

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LIST OF ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
AC	Air Conditioning
ACH	Air Changes per Hour
AH	Affordable Housing
AHP	Affordable Housing in Partnership
ARHC	Affordable Rental Housing Complex
ASHRAE	American Society for Heating, Refrigerating and Air-Conditioning Engineers
BAU	Business-As-Usual
BEE	Bureau of Energy Efficiency
BHK	Bedroom, Hall, & Kitchen
BLDC	Brushless Direct Current
BMTPC	Building Materials and Technology Promotion Council
CFC	Chlorofluorocarbon
CLSS	Credit Linked Subsidy Scheme
COVID-19	Coronavirus Disease 2019
CTC	Carbon Tetrachloride
DC	Direct Current
DEC	Direct Evaporative Cooler
DOAS	Dedicated Outdoor Air System
ECBC-R	Energy Conservation Building Code-Residential
ECM	Energy Conservation Measure
EE	Energy Efficiency
ENS	Eco-Niwas Samhita
EPA	Environmental Protection Act
EPI	Energy Performance Index
EPS	Expanded Polystyrene
EWS	Economically Weaker Section
FAR	Floor Area Ratio
GFRC	Glass Fiber Reinforced Concrete
GHG	Green House Gas
GoI	Government of India
GRIHA	Green Rating for Integrated Habitat Assessment
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFA	Housing for All
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HPMP	HCFC Phase-out Management Plan
HVAC	Heating, Ventilation, and Air Conditioning
ICAP	India Cooling Action Plan
IDEC	Indirect-Direct Evaporative Cooler
IEC	Indirect Evaporative Cooler
IGBC	Indian Green Building Council
IMAC	Indian Model for Adaptive Comfort
INR	Indian Rupee
IT	Information Technology
K	Kelvin

kWH	Kilowatt-Hour
LEED	Leadership in Energy and Environmental Design
LIG	Low-Income Group
m^2	Square Metre
MIG	Medium-Income Group
mm	Millimetre
MNRE	Ministry of New and Renewable Energy
MoEF&CC	Ministry of Environment, Forest & Climate Change
NBC	National Building Code
NGO	Non-Governmental Organisation
NURHP	National Urban Rental Housing Policy
O&M	Operation & Maintenance
ODP	Ozone Depleting Potential
ODS	Ozone Depleting Substances
PMAY-U	Pradhan Mantri Awas Yojana-Urban
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPP	People, Planet, Profit
PVC	Polyvinyl Chloride
RAC	Room Air Conditioner
RAY	Rajiv Awas Yojana
RCC	Reinforced Cement Concrete
RETV	Residential Envelope Transmittance Value
SCM	Smart Cities Mission
SDI	Solar Decathlon India
SHGC	Solar Heat Gain Coefficient
SRI	Solar Reflectance Index
TAG	Technical Action Group
TERI	The Energy and Resources Institute
TR	Tonne of Refrigeration
TWh	Terawatt-Hour
UHIE	Urban Heat Island Effect
USD	United States Dollar
UT	Union Territory
UV	Ultraviolet
VLT	Visible Light Transmittance
W	Watt
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio
XPS	Extruded Polystyren

Affordable housing is a crucial sub-sector of housing, considering the lack of universal access to housing in the country and ongoing PMAY programme. **The affordable housing sector would benefit from using climate-appropriate strategies and energy-efficient building designs** to construct houses for the EWS and LIG segments.

EXECUTIVE SUMMARY

The Pradhan Mantri Awas Yojana (PMAY), a flagship programme of the Government of India, aims to provide affordable housing to the urban and rural poor. On June 25, 2015, the PMAY-Urban (PMAY-U) was launched with a mission to provide housing for all in urban areas by 2022. The mission focuses on building affordable housing faster and delivering these units at an affordable price within the specified period. The India Cooling Action Plan (ICAP), launched by the Ozone Cell, Ministry of Environment, Forest and Climate Change (MoEF&CC), focuses on reducing cooling, refrigerant, and energy demand over the next twenty years and decreasing cooling demand from the housing sector, including low-income groups (LIGs), economically weaker sections (EWSs), and affordable housing. The overarching goal of ICAP is to provide sustainable cooling and thermal comfort for all, while securing environmental and socioeconomic benefits for the society.

Urban inequality accounts for a low per capita level of energy for space cooling. Currently, India consumes 69 kilowatt-hours (kWh) per capita for space cooling, compared to the world average of 272 kWh, making it one of the lowest in the world. In the absence of additional policy interventions and continuation of the business-as-usual (BAU) scenario, room air conditioner (RAC) penetration is expected to rapidly increase in India, reaching somewhere between 190 and 239 million units by 2030[1], amounting to about 152 terawatt-hours (TWh) in annual energy consumption. The consumption of refrigerants required for space cooling is thus projected to increase from ~70 million tonnes of refrigeration (TR) in 2017-18 to ~245 million TR in 2027-28, out of which 85% of the demand is expected to be from RACs. The exponential growth in the RAC stock will also give rise to the heat island effect, which is going to highly impact the most vulnerable sector, i.e the economically weaker section of society in the affordable housing sector.

Affordable housing is a crucial sub-sector, considering the deficiency in access to housing across the country and the ongoing PMAY programme. A large proportion of the PMAY mission target is likely to be self-built housing. Fund allocation for exclusive studies on energy efficiency measures and thermal comfort enhancement for each housing project will not be possible. To design and construct climate-appropriate and energy-efficient affordable houses for the EWS and LIG segments, a prescriptive set of recommendations in line with a national standard or code like the Eco-Niwas Samhita is needed.

The Pradhan Mantri Awas Yojana (PMAY), a flagship programme of the Government of India, aims to provide affordable housing to the urban and rural poor. On June 25, 2015, the PMAY-Urban (PMAY-U) was launched with a mission to provide housing for all in urban areas by 2022. The mission focuses on building affordable housing faster and delivering these units at an affordable price within the specified period.

1 Cell and Ministry of Environment Forest & Climate Change Government of India.

Such recommendations need to be focused on preventing the additional introduction of energy-intensive space cooling appliances in any possible form, while simultaneously addressing energy efficiency and thermal comfort. Thus, addressing comfort issues for affordable housing beneficiaries through thermally efficient construction and promotion of refrigerant-free low-energy cooling technologies is necessary to support the Kigali Amendment. Feasible and cautious recommendations need to be put forth in this regard.

Various ongoing policy initiatives were reviewed for this study, including the Eco-Niwas Samhita (ENS), ICAP, and Hydrochlorofluorocarbon Phase-out Management Plan (HPMP). The ICAP has already laid out sector-wide priorities and pathways for interventions. Aligned closely with the recommendations of ICAP, the project objective is to take an integrated approach to advance the agenda of energy-efficient & environmentally-friendly cooling systems. This study aimed to enable relevant stakeholders like investors, developers, and architects to take the initial step towards building sustainability, considering fundamentally enhanced cooling, low energy bills for occupants, low construction costs and high-performing buildings for investors. The study addresses this by recommending strategies to reduce the cooling demand and identifying non-ozone depleting substances (ODS) and low global warming potential (GWP) solutions and technologies that can help reduce the overall cooling load and refrigerant requirement. Since refrigerant-based technologies are energy- and cost-intensive, this study encompasses passive strategies and low-energy cooling technologies for the residential sector, specifically focusing on the EWS and LIG segments. Typical BAU design and construction patterns were studied to understand the existing context. It was identified that current design and construction practices are not streamlined for affordable housing and, therefore, this report recommends passive strategies to reduce heat gain from the building envelope and low-energy cooling technologies to enhance thermal comfort, considering affordable housing and cost-related aspects.

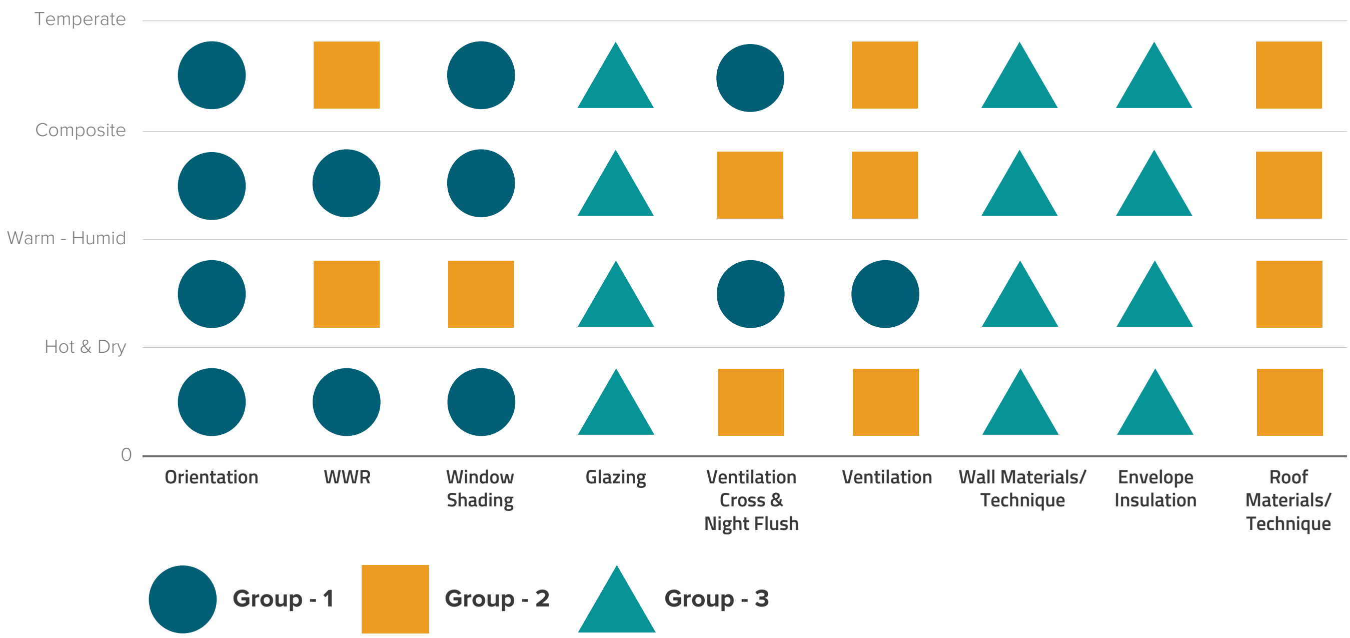
Various ongoing policy initiatives were reviewed for this study, including the Eco-Niwas Samhita (ENS), ICAP, and Hydrochlorofluorocarbon Phase-out Management Plan (HPMP). The ICAP has already laid out sector-wide priorities and pathways for interventions. Aligned closely with the recommendations of ICAP, the project objective is to take an integrated approach to advance the agenda of energy-efficient & environmentally-friendly cooling systems.

The study entailed collecting, collating, and analysing information through secondary desk research, along with stakeholder consultations with sectoral experts. Conclusions were drawn on hydrochlorofluorocarbon (HCFC)-based applications in the building sector. The results from secondary research and expert stakeholder consultations were mapped and supported in validating the findings.

Figure A, Table A, and Table B can assist investors and developers in decision-making on incorporating energy efficiency into affordable housing; they focus on passive strategies, low-energy cooling strategies, and building material selection, respectively.

Figure A depicts the priority ranking of various strategies based on climatic conditions. These priority groups are a result of performance-cost optimisation based on expert consultations after secondary literature reviews.

Figure A Climate-wise passive strategy prioritisation



Group 1 indicates the recommended strategies that should be considered first followed by Group 2 and Group 3 in sequential order considering cooling load and cost.

Group 1 indicates the recommended strategies that should be considered first followed by Group 2 and Group 3 in sequential order considering cooling load and cost. Recommendations here are not classified as 'recommended' and 'not recommended'; rather, they are ranked based on their potential to enhance building energy efficiency in the given climate. Table A shows the final ranking of recommended low-energy cooling strategies. As low-energy cooling strategies are less feasible in affordable housing than passive strategies, this study shortlisted the two most relevant strategies: super-efficient fans and evaporative cooling (direct, indirect, & 2-stage). Grouping recommendations is less relevant in this context, and the strategies were consequently ranked for all climates, unlike passive strategies.

Table A Final climate-wise ranking of low-energy cooling strategies

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

Table B shows envelope material recommendations for the most recommended materials for affordable housing. It was found that autoclaved aerated concrete (AAC) and hollow blocks are suitable in all climates. Other materials like clay bricks, cellular concrete, and fly ash are ideal in most climates.

Table B Envelope material recommendations

	Hot & dry	Warm-humid	Composite	Temperate
Wall Materials	AAC	AAC	AAC	AAC
	Clay bricks	Clay bricks	Cellular concrete	Clay bricks
	Hollow bricks	Hollow bricks	Hollow bricks	Hollow bricks
	Fly ash	Cellular concrete	Fly ash	Fly ash
Roof Materials	Roof - all climates			
	Roof material	Lime concrete, mud-phuska		
	Roof 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 absence of insulation		
Envelope Insulation	Envelope insulation - all climates			
	Insulation material	EPS, fiberglass, mineral wool		
	Additional recommendations	Insulation decisions depend on cost Insulation for roof more preferred than walls Simple insulation will suffice for basic thermal comfort		

These recommendations regarding priority groups and ranking are intended to assist stakeholders in taking a step towards building sustainability. The priority groups do not mean that Groups 2 and 3 should be neglected, but it is recommended to start with Group 1 initially. To enable this, incentives need to be provided to investors. While there are incentives and subsidy schemes to promote affordable housing, there are no incentives for energy efficiency in the affordable housing sector. The one-on-one expert stakeholder consultation led to numerous learnings in terms of technical responses which can be incorporated into future research and development.

It was found that autoclaved aerated concrete (AAC) and hollow blocks are suitable in all climates. Other materials like clay bricks, cellular concrete, and fly ash are ideal in most climates.

01 INTRODUCTION

The Pradhan Mantri Awas Yojana (PMAY), a flagship programme of the Government of India, aims to provide affordable housing to the urban and rural poor. On June 25, 2015, the PMAY-Urban (PMAY-U) was launched with a mission to provide housing for all in urban areas by 2022. The mission focuses on building affordable housing faster and delivering these units at an affordable price within the specified period[2]. The affordable housing narrative is currently driven by the link between income, built space provisions, and the cost of the dwelling units as the determining criteria for affordable housing. However, thermal comfort needs to be mainstreamed when designing and developing affordable housing schemes.

The income categories served under the PMAY-U are the economically weaker sections (EWS), low-income groups (LIG-1 and LIG-II), and medium-income groups (MIGs). As established in the India Cooling Action Plan (ICAP), these government schemes can benefit from climate-appropriate and energy-efficient building design in housing construction for the EWS and LIG segments. ICAP, launched by the Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India, has also recommended accelerating the cooling load reduction in the building sector through fast-tracked implementation of building energy codes, adoption of adaptive thermal comfort standards, the ratcheting up of room air conditioner (RAC) and fan energy efficiency, and enhancing consumer awareness through the eco-labelling of cooling products. In this regard, the energy-efficient building guidelines of the Eco-Niwas Samhita (ENS) could be enforced. To meet the cooling demand, cities like Delhi and Mumbai use over half of their electricity to run air conditioners in the hot season[3]. RACs constitute the dominant share of the sector's cooling energy consumption—around 40% in 2017-18, and this figure is projected to increase to around 50% in 2037-38[4]. Despite the twofold increase in the sale of RACs, penetration remains relatively low, at around 7-9%, but it is expected to increase over the next decade[5]. It is important to note that most EWS households use ceiling fans for thermal comfort and contribute the least to power demand.

RACs constitute the dominant share of the sector's cooling energy consumption—around 40% in 2017-18, and this figure is projected to increase to around 50% in 2037-38.

Furthermore, AC-induced urban heat islands are projected to increase the vulnerability of urban populations, especially the poor, potentially leading to heat-related health impacts in the future.

2 Ministry of Housing & Urban Poverty Alleviation, Government of India, "Pradhan Mantri Awas Yojana - Housing for All (Urban) - Scheme Guidelines 2015" (2015).

3 Nihar Shah et al., "Considerations in Standardization for Demand Ready Air Conditioners in India," 2014, 1–7, https://doi.org/10.13140/RG.2.1.3031.2486.

4 Ozone Cell, MoEF&CC, Government of India, "India Cooling Action Plan," 2019.

5 Ozone Cell, MoEF&CC, Government of India.

Global warming and heat waves affecting people in India are constantly in the news [6 7 8 9 10]. Developing thermally comfortable housing for the urban poor is therefore essential from a resilience perspective, with profound health implications. As such, the MoEF&CC has focused its attention on EWS and LIG housing in the ICAP to strengthen its position in India's evolving cooling narrative.

The ICAP[11] estimates that the refrigerant-based AC stock of ~70 million tonnes of refrigeration (TR) is likely to triple over the next decade and increase by a factor of ten over the next two decades. RACs, mainly in the residential sector, will continue to dominate, at 80-90% share. Beyond severe environmental implications, this unchecked surge in RAC deployment will create stark social inequity. It is necessary to address this problem with a clear solution that does not create new problems. Tackling comfort issues for affordable housing dwellers through thermally-efficient construction or using RACs with HCFC-based refrigerants might threaten the environment and go against the Kigali Amendment. In this context, feasible and cautious recommendations are needed.

The ICAP estimates that the refrigerant-based AC stock of ~70 million tonnes of refrigeration (TR) is likely to triple over the next decade and increase by a factor of ten over the next two decades.

In 2018, Alliance for an Energy Efficient Economy (AEEE) carried out a detailed review of the regulatory provisions in the PMAY, assessed the mission targets and progress, and highlighted appropriate energy optimisation strategies for the affordable housing sector[12] . This was a push for PMAY-U to include energy efficiency in mainstream affordable housing provision in India. 'Housing for all' can be a more feasible initiative and mission when supplemented with 'comfort for all', which enhances living conditions and eventually increases the occupancy rate and usage of affordable housing.

The following are the critical reasons for undertaking the study:

- ➔ The mission has diverse housing and project types, and one solution will not be universally applicable.
- ➔ The rate of project approval and construction processes and timeline provides a window of opportunity to incorporate thermal comfort criteria and energy optimisation strategies to design and construct affordable housing.
- ➔ Mainstreaming energy optimisation requires a more vital link between research, practice, and policy design.

A large proportion of the mission target is likely to be self-built housing. Fund allocation for exclusive studies on energy efficiency measures for each housing project will not be possible.

A large proportion of the mission target is likely to be self-built housing. 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 ENS is needed.

6 National Herald, "Parts of India to See Deadly Heat Waves in Coming Decades_ Study," n.d.

7 The Indian Express, "Heat Wave, Hot Days and Warm Nights over Delhi, Chandigarh, Haryana, UP", IMD, India News, The Indian Express, n.d.

8 The Indian Express, "In India, over 75% Districts Hotspots of Extreme Weather Events, Finds Study", India News, The Indian Express, n.d.

9 The Indian Express, "Heat Wave Continues in Rajasthan as Temperatures Glide over 47 Degrees" Weather News, The Indian Express, n.d.

10 The Hindu, "Arctic Warming Is Causing Heat Waves in India_ Study", The Hindu, n.d.

11 Ozone Cell, Ministry of Environment, Forest & Climate Change, Government of India, "India Cooling Action Plan."

12 G. Kumar, S. Singh, M. Chandiwala, S. Sneha, & G. George, "Mainstreaming Thermal Comfort for All and Resource Efficiency in Affordable Housing," 2018.

Hence, a fundamentally prescriptive set of recommendations in line with a national standard or code like the ENS is needed.

1.1 Background

Over the past decade, the world has witnessed a record frequency and temperatures of heat waves, which have resulted in over 6000 casualties. Rising temperatures in urban centres increase the demand for cooling and have moderate to severe negative impacts. AC-induced urban heat islands are projected to increase the vulnerability of urban populations, especially the poor, potentially leading to heat-related health impacts in the future. These impacts include issues such as poor public health, reduced workforce productivity, and poor air quality, which disproportionately affect the LIG and EWS leading to greater urban inequality.

On the one hand, India is one of the fastest-growing and largest economies in the world. On the other, the growth is not equally distributed. Overall, India has a very low per capita level of energy consumption for space cooling—69 kilowatt-hours (kWh) per capita, compared to the world average of 272 kWh, making it one of the lowest globally[13].

According to macroeconomic estimates, the per capita income in India will rise to about USD 5,700 (INR 4.15 lakhs) in 2030[14] from USD 2,104 (INR 1.5 lakhs) in 2019. This increase would alter the quality of life in Indian cities and enhance citizens' socio-economic status. The projected growth, coupled with the rising temperatures in Indian cities, could significantly alter urban consumption patterns, directly impacting the rise in cooling demand. In the absence of additional policy measures

13 Ozone Cell, Ministry of Environment, Forest & Climate Change, Government of India, "India Cooling Action Plan."

14 Bloomberg, "India Insight: $10 Trillion GDP by 2030? Not Quite, but Almost | Bloomberg Professional Services," 2019, https://www.bloomberg.com/professional/blog/india-insight-10-trillion-gdp-by-2030-not-quite-but-almost/.

and continuation of the business-as-usual (BAU) scenario, RAC penetration is expected to rapidly increase in India, reaching somewhere between 190 and 239 million units by 2030[15], amounting to about 152 terawatt-hours (TWh) in annual energy consumption. To address the growing energy demand and thermal comfort challenges in the affordable housing sector, it is vital to examine India's current policy initiatives and housing scenario. Solutions need to be developed to prevent the additional introduction of HCFCs in any possible form, while simultaneously addressing energy efficiency and thermal comfort. Various ongoing policy initiatives were reviewed for this study, including the ENS, ICAP, and Hydrochlorofluorocarbon Phase-out Management Plan (HPMP).

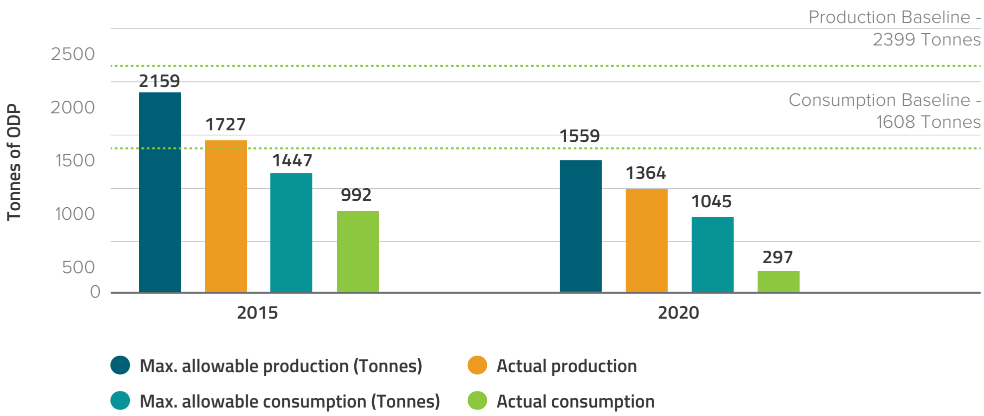
Solutions need to be developed to prevent the additional introduction of HCFCs in any possible form, while simultaneously addressing energy efficiency and thermal comfort.

1.2 Impact of buildings on ozone depletion

Hydrochlorofluorocarbons (HCFCs) had been used as low-ozone depleting potential (ODP) transitional substances to replace high-ODP ozone depleting substances (ODS) such as chlorofluorocarbons (CFCs), carbon tetrachloride (CTC), and halons in various applications, including refrigeration & air conditioning, foam blowing, aerosols, solvents, and firefighting materials. Commonly used HCFCs include HCFC-22, HCFC-141b, HCFC-142b, HCFC-123, HCFC-124, and HCFC-225.

India is currently phasing out HCFCs in production and consumption as per the accelerated phase-out schedule of the Montreal Protocol, shown in Figure 1.

Figure 1 : HCFC Phase-out in India



The baseline values of HCFC production and consumption are 2399.5 ODP tonnes and 1608.20 ODP tonnes, respectively. As per the accelerated phase-out schedule, the maximum allowable production limit for 2015 and 2020 is 2159.55 and 1559.655 ODP tonnes, respectively. India is well within the limit in production, as it only produced 1727.62 ODP tonnes in 2015 and 1364.71 ODP tonnes in 2020. Similarly, as per the Montreal Protocol reduction schedule, the maximum allowable consumption of HCFCs for 2015 and 2020 is 1447.38 ODP tonnes and 1045.33 ODP tonnes, respectively, whereas India consumed 992.54 ODP tonnes in 2015 and 297.505 ODP tonnes in 2020.

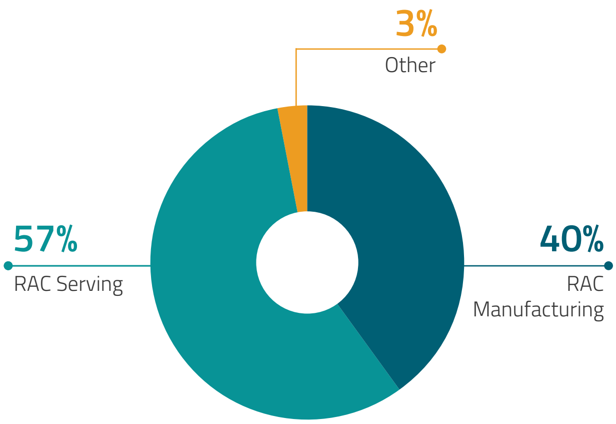
The baseline values of HCFC production and consumption are 2399.5 ODP tonnes and 1608.20 ODP tonnes, respectively.

15 Ozone Cell, Ministry of Environment, Forest & Climate Change, Government of India, "India Cooling Action Plan."

Of the HCFC consumption in 2020, **40% is from the RAC manufacturing sector, 57% is from the RAC servicing sector, and 3% is from other sectors,** as shown in Figure 2.

The complete phase-out of HCFC production and consumption is targeted for 2030, with a service tail of 2.5% of the annual average from 2030 to 2040. India has proactively phased out HCFC-141 b completely in the foam manufacturing sector as of January 1st, 2020, as part of the implementation of HPMP Stage II. Of the HCFC consumption in 2020, 40% is from the RAC manufacturing sector, 57% is from the RAC servicing sector, and 3% is from other sectors, as shown in Figure 2.

Figure 2 : Sector-wise distribution of HCFC consumption in India in 2020



1.3 India's affordable housing sector at a glance

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[16]. 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, 96% is required by EWS and LIG households[17].

1.3.1 Affordable housing shortage in India

The housing shortage distribution across various income categories is shown in Table 1. The highest shortage across income categories is a 56% deficit for the EWS segment.

Table 1 : Housing shortage across income groups in India

Category	2012 distribution of housing shortage	
	No. (millions)	Percentage
EWS	10.55	56.18%
LIG	7.41	39.44%
MIG and above	0.82	4.38%

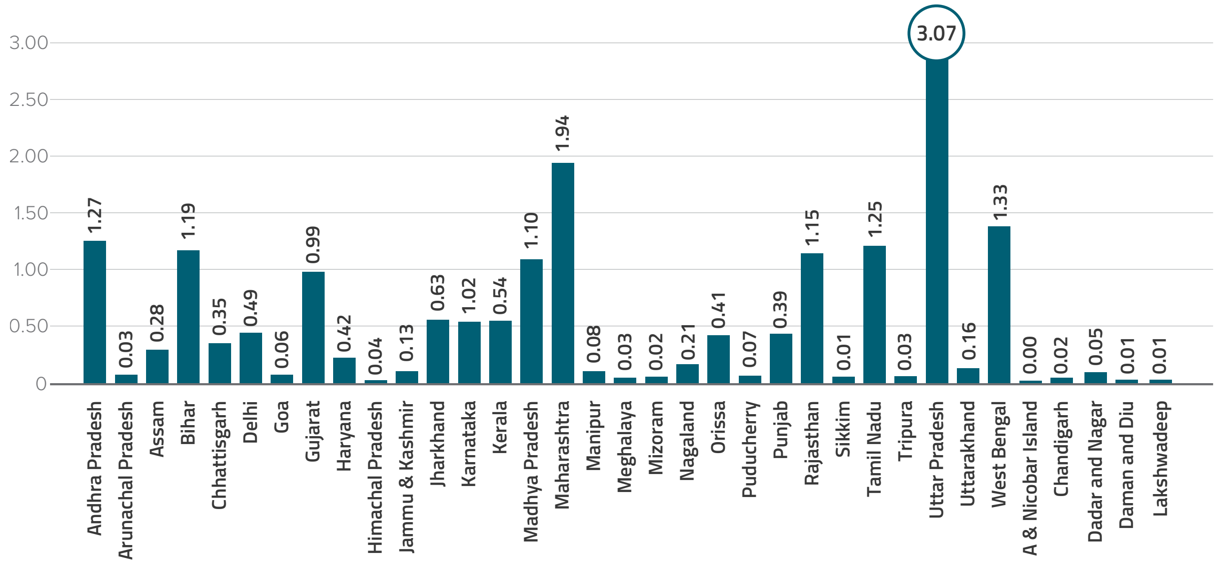
16 Planning Commission, Government of India, Twelfth Five Year Plan (2012–2017): Faster, More Inclusive and Sustainable Growth, vol. 1, 2012.

17 Ministry of Housing and Urban Poverty Alleviation, Government of India, and National Buildings Organisation, "Report of The Technical Group On Urban Housing Shortage (TG-12) (2012-17)," MoHUPA, 2012.

The affordable housing shortage in urban India stood at 18.78 million dwelling units as per the 12th five-year plan in 2012. It is expected to reach 44-48 million dwelling units by 2022. The urban housing shortage can be broken down into various typologies of houses, including non-serviceable katcha, obsolescent houses, congested houses that require new houses to be built, and homeless conditions.

A majority of the shortage (14.99 million households) are living in congested houses, requiring new houses to be built. This shortage is distributed across various Indian states. Figure 3 shows that Uttar Pradesh has the highest shortage (3.07 million units), followed by Maharashtra with 1.94 million and West Bengal with 1.33 million.

Figure 3 : State-wise urban housing shortage (millions)[18]



As a response to the growing housing deficit, the Government of India (GoI) launched the Housing for All by 2022 (i.e. PMAY) in 2015, with a vision to provide every family with a pucca (type of construction deemed permanent) house with a water connection, toilet facilities, and 24x7 electricity supply [19]. Against the 18.78 million housing unit demand in urban areas, PMAY-U aims to build 12 million housing units by 2022.

As a response to the growing housing deficit, the Government of India (GoI) launched the Housing for All by 2022 (i.e. PMAY) in 2015, with a vision to provide every family with a pucca (type of construction deemed permanent) house with a water connection, toilet facilities, and 24x7 electricity supply.

1.3.2 Pradhan Mantri Awas Yojna (PMAY)-Urban

The focus of the PMAY mission is to build housing units quickly and deliver them at an affordable price within the specified period. 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 of affordable housing. There is limited or no focus on qualitative aspects that determine housing livability and occupant productivity.

18 Ministry of Housing and Urban Poverty Alleviation, Government of India, and National Buildings Organisation, "Report of The Technical Group On Urban Housing Shortage (TG-12) (2012-17)," MoHUPA, 2012.

19 Anukriti Pathak, Tarun Garg, and Satish Kumar, "A Policy Strategy for Decarbonising the Building Sector-Facilitating Eco-Niwas Samhita Implementation in Affordable Housing," 2020.

India is now in Phase III of the mission. **As of January 2020, INR 1630 billion has been sanctioned, and INR 640 billion has been released. 10.3 million houses have been sanctioned as of January 2020, out of which 3.2 million houses have been completed (30% of the total sanctioned houses.)**

'Housing for All' has 3 phases[20]:

1. Phase I (April 2015-March 2017) covered 100 selected cities in states/union territories (UTs) as per their willingness.

2. Phase II (April 2017-March 2019) covered 200 additional cities.

3. Phase III (April 2019 - March 2022) aims to cover all remaining cities.

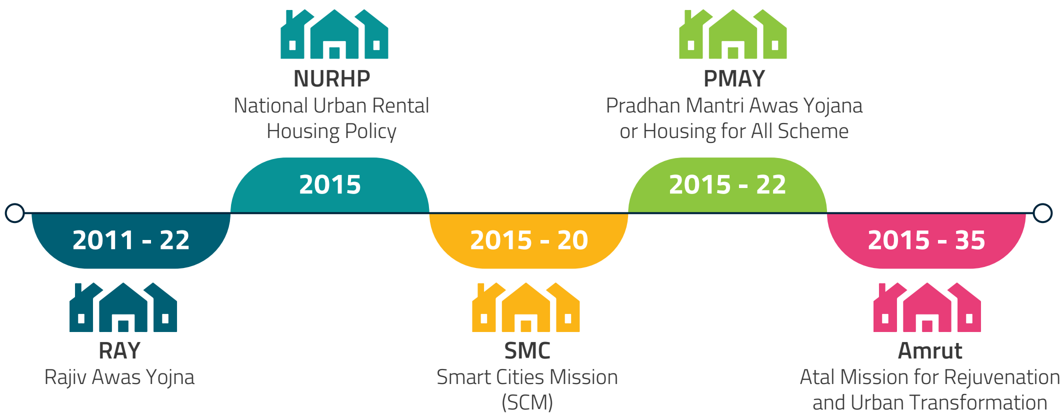
India is now in Phase III of the mission. As of January 2020, INR 1630 billion has been sanctioned, and INR 640 billion has been released. 10.3 million houses have been sanctioned as of January 2020, out of which 3.2 million houses have been completed (30% of the total sanctioned houses.)[21] To enable structured implementation of housing for all, households are divided into various economic categories based on their annual income: EWS, LIGs, and MIGs. The affordable housing PMAY-U status as of June 2021 is the following[22]:

- ➔ 11.29 million houses sanctioned
- ➔ 8.32 million houses grounded
- ➔ 5 million houses completed.

1.3.3 Ongoing affordable housing-related policies and schemes in India

The recent ongoing schemes and policies with a link to affordable housing are depicted in Figure 4. They address different challenges on similar lines, working towards the overall target of 'housing for all.

Figure 4 : Indian affordable housing-related schemes and policies



A brief description of these policies and schemes is given in Table 2, including their main focus and objective.

20 Ministry of Housing & Urban Poverty Alleviation, Government of India, Pradhan Mantri Awas Yojana - Housing for All (Urban) - Scheme Guidelines 2015.

21 ICRA and FICCI, "Affordable Housing," 2020.

22 "PMAY-HFA (Urban)," n.d.

Table 2 : Affordable housing-related schemes and policies in India23

Sl.no	India- relevant ongoing Scheme/policy
1	**Rajiv Awas Yojana (RAY), originally 2011- 2022, subsumed under PMAY-HFA (U) in 2015** - focused on provision of 'housing for all' to the urban poor through the Affordable Housing in Partnership (AHP) scheme. The preparatory phase (2011-2013) was the RAY, and the second phase from 2014-2022 is the PMAY.
2	**National Urban Rental Housing Policy (NURHP), 2015** - intends to promote rental housing for the poor. These housing units are usually owned by non-governmental organisations (NGOs), private sector entities, cooperatives, and industries. The policy seeks to facilitate various types of public-private partnerships for the promotion of rental housing in the country, to achieve the overall goal of housing for all by 2022.
3	**Smart Cities Mission (SCM), 2015-2020** - aimed to promote cities that provide core infrastructure, sustainable transport, affordable housing, information technology (IT) connectivity and digitisation, a safe, secure, & sustain-able environment, and good governance.
4	**Pradhan Mantri Awas Yojana (PMAY) OR Housing for All Scheme (HFA), 2015-2022** - aims to provide housing for all by 2022 to the urban poor through slum rehabilitation and promotion of affordable housing for EWS through the Credit Linked Subsidy Scheme (CLSS) and public-private partnerships.
5	**Atal Mission for Rejuvenation and Urban Transformation (AMRUT), 2015-2035** - aimed to provide basic infra-structure and increase green space through parks, green spaces, and recreational centres. Five hundred cities with a population >1 lakh are to be covered.

1.3.4 National initiatives to reduce the cooling load in buildings

To tackle the growing cooling demand and mainstream energy efficiency in residential buildings, the Energy Conservation Building Code for Residential Buildings (ECBC-R), now called the Eco-Niwas Samhita, was launched by the Ministry of Power, Government of India in 2018. Furthermore, the HPMP[24] and ICAP[25] were launched by the MoEF&CC, Government of India, to tackle the impact of climate change in India. These are the key policy initiatives that link energy efficiency to thermal comfort. The relevance of these policy initiatives to affordable housing and energy efficiency is summarised in Table 3 below.

23 Gregor Herda et al., "Sustainable Social Housing in India: Definition, Challenges and Opportunities -Technical Report," no. May (2017).

24 Ozone Cell, MoEF&CC, Government of India.

25 Ozone Cell, Ministry of Environment, Forest & Climate Change, Government of India, "India Cooling Action Plan."

Table 3 : Policies to reduce cooling energy demand and HCFC phase-out in the built environment

Policies tackling ozone depletion and energy efficiency in affordable housing	Relevance to HCFC phase-out and affordable housing
HCFC Phase-out Management Plan[26]	▪ HPMP Stage-1 (2012-2016) phased out 341.77 ODP tonnes of HCFCs. Out of this, 310.53 OPD tonnes of HCFC 141b have been phased out in the foam manufacturing sector and 31.24 ODP tonnes of HCFC-22, in the RAC servicing sector. ▪ HPMP Stage II was launched in 2017 by the MoEF&CC and aims to phase out six major RAC brands by 2022 and train 17,000 RAC technicians. It also targets converting ten manufacturing lines in six AC manufacturing enterprises from HCFC-22 to HFC-32 refrigerant (a non-ODS and low-global warming potential (GWP) refrigerant) and increasing energy efficiency in the building sector.
India Cooling Action Plan[27]	▪ MoEF&CC developed the ICAP in March 2019. ▪ Provides a 20-year perspective on addressing cooling demand across all sectors and enabling access to sustainable cooling. ▪ One of the goals of ICAP is to reduce refrigerant demand by 25-30% by 2037-38. ▪ ICAP has formed synergies with other government initiatives and international commitments in order to develop a holistic approach and achieve higher impact than if formulating proposals in isolation. ▪ ICAP also supports and cites HPMP Stage1 and HPMP Stage II and the phase-down in the Kigali amendment to the Montreal protocol. ▪ The following are key short- and medium-term recommendations relevant to the residential sector: 1. Allocate government funding and support to targeted programmes to ensure adequate cooling for LIGs and EWS; introduce climate-appropriate building design & construction in affordable housing under PMAY 2. Mandatory minimum indoor temperature settings (adaptive thermal comfort standards) 3. Ratchet up minimum energy performance standards (MEPS) for RACs 4. Mandatory star labelling for fans and introduction of MEPS for evaporative coolers 5. Mandatory public procurement guidelines for energy-efficient ACs, fans, chillers, etc. (low- GWP options wherever available) 6. Incentives coupled with awareness campaigns to drive market demand for energy-efficient cooling appliances and equipment 7. All new construction—both residential and commercial—should be 100% code compliant. The minimum stringency levels of ECBC compliance should be revised over time to ECBC+ and Super ECBC requirements.

26 Ministry of Environment Forest & Climate Change Government of India, "HCFC PHASE-OUT AND ENERGY EFFICIENCY IN BUILDINGS" (New Delhi, 2017).

27 MoEF&CC, "India Cooling Action Plan," 2019, http://ozonecell.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf.

Policies tackling ozone depletion and energy efficiency in affordable housing	Relevance to HCFC phase-out and affordable housing
Eco Niwas Samhita 2018 - Part 1: Building envelope[28]	■ Part 1 focuses on building design and building envelope-related interventions. The code is applicable for plot areas above 500 square metres (m2). ■ Part 2 focuses on electromechanical systems and is still under development. ■ Further to the launch of code, Bureau of Energy Efficiency (BEE) recently launched a Handbook of Replicable Designs for Energy Efficient Residential Buildings29, the designs and templates of which are included in Annexure-III of this report.

As per the Ozone Depleting Substances (Regulation and Control) Rules, 2000 and its amendments, the phase-out date for manufacturing all other equipment or products containing HCFCs is 1st January 2025. Green building rating systems are also changing the landscape of energy efficiency in affordable housing. Table 4 discusses and compares various green building rating systems prevalent in India and their relevance to energy efficiency and HCFC phase-out. Green building rating systems evaluate a building against various criteria covering site planning, energy performance, renewable energy, water and waste management, indoor environmental quality, material and resources, and other socioeconomic aspects. The rating systems act as a catalyst to create the market and bring awareness amongst various stakeholder groups on energy efficiency.

The phase-out date for manufacturing all other equipment or products containing HCFCs is 1st January 2025.

Table 4 : Green building rating systems in India

Green building rating system	Relevance for affordable housing
GRIHA for Affordable Housing[30]	■ The 'Green Rating for Integrated Habitat Assessment' (GRIHA) was launched in 2005, together with the Ministry of New and Renewable Energy (MNRE) and Government of India and developed by The Energy and Resource Institute (TERI). ■ GRIHA for Affordable Housing is aligned with the PMAY. ■ It dedicates 25 out of 104 points to 'Energy and occupant comfort'. Additionally, it dedicates six points to 'low impact design'. Mandatory criterion 22-'zero ODP materials' ban the usage of CFCs and HCFCs in building insulation and heating, ventilation, and air conditioning (HVAC) equipment.
IGBC Affordable Housing	■ The Indian Green Building Council (IGBC) for Affordable Housing was launched in May 2017 exclusively for affordable housing (IGBC AH). ■ Twelve out of 100 points fall under the 'Energy Conservation' module. Additionally, it dedicates 13 points to various issues like local/alternate materials, daylighting, cross and fresh ventilation, and roof surface treatment.

28 Bureau of Energy Efficiency, Eco-Niwas Samhita, Ministry of Power, Government of India, vol. 1, 2018.

29 Bureau of Energy Efficiency (BEE), Handbook of Replicable Designs for Energy Efficient Residential Buildings, 2021.

30 TERI, "GRIHA for Affordable Housing," GRIHA Council and The Energy and Resources Institute (New Delhi, 2017).

LEED Homes [31] [32]	■ The Leadership in Energy and Environmental Design (LEED) for Homes is a rating system dedicated to residential building design and construction. ■ Thirty-seven out of 110 points fall under the 'Energy and Atmosphere' module, which is exclusively for residential energy efficiency. Additionally, it also includes three points on 'enhanced ventilation'. ■ However, there is no mention about HCFCs, CFCs, ODPs, or GWP.

1.3.5 Typical affordable housing construction

At the outset, the bulk of housing for the low-income segment in India has employed conventional construction technologies to create the building stock. The structural design of these buildings is based on reinforced cement-concrete (RCC) framed construction. Consequently, cement, steel, and masonry are the principal building materials used for the building envelope. LIG housing typology is predominantly low-rise up to G+6, with (up to) G+3 being the most common typology. Each floor plate has a cluster of four dwelling units with common staircase-corridor access. Table 5 shows the most common specifications of construction materials that are used in low-income housing in most states in India[33]. Most construction materials in India are purchased from the informal sector; this must be considered during material selection and its impact on cost, quality, and environmental performance.

Table 5 : Construction material specifications for low-income houses in India[34]

Building element	Construction materials specifications
Structure	1 Most common for more than G+1 structure - RCC frame structure as per codal provisions for seismic design, using M20 strength concrete 2 Optional for up to G+1 – load bearing construction with strip footing and RCC plinth beams
Building envelope	■ 230/250 millimetre (mm) thick burnt clay brick masonry in cement-sand mortar (1:6) ■ 150-200 mm thick concrete block masonry in cement mortar (1:6) ■ Fly ash bricks have become a feasible alternative to burnt clay bricks over the last few years in government projects, wherever the project is within about 100 kilometres (km) of the power plant.
Flooring	■ Ceramic/vitrified tiles ■ Locally available (pre-polished) 20-30 mm thick stone tiles ■ Plain cement concrete floor
Openings	■ Pressed steel door-window frames (125 mm x 65 mm double rebate or 100 mm x 50 mm single rebate) ■ Solid core flush doors 30 mm thick or polyvinyl chloride (PVC) shutter for internal door ■ 6 mm thick float glass for glazed parts, 450 mm wide RCC sunshades for windows

31 USGBC, "LEED BD+C v4 New Construction," vol. 3096, 2013.

32 USGBC, LEED for Homes Design and Construction (GBCI, 2017).

33 Herda et al., "Sustainable Social Housing in India: Definition, Challenges and Opportunities -Technical Report."

34 Herda et al.

Building element	Construction materials specifications
Finishes	■ Cement-sand plaster 20 mm thick (external), 15 mm thick (internal) ■ White cement-based putty ■ Cement paint-external and internal or whitewash-internal

A study by the Oxford Brooke's University, Development Alternatives, TERI, and United Nations Habitat[35] selected five states (Rajasthan, Andhra Pradesh, Karnataka, Uttar Pradesh, & Uttarakhand) to review the social housing sector based on specific set criteria. The states were selected based on completed housing projects under PMAY-U. Up to now, these have been limited to demonstration projects with technical support from various institutions. Some of these technologies have been certified by the Building Materials and Technology Promotions Council (BMPTC), although they are yet to be absorbed into building codes and byelaws[36].

Construction costs are a significant component in low-income and affordable housing projects, accounting for about 60% of the project cost. In this regard, it is vital to select the appropriate construction technology to achieve cost-effectiveness. A 15-20% reduction in construction costs can be achieved by adopting the alternative construction technologies for walls and roofs listed in Table 6.

A 15-20% reduction in construction costs can be achieved by adopting the alternative construction technologies for walls and roofs

Table 6 : Alternative construction technologies for walls and roofs in affordable housing[37]

Alternative building material/ system	Application in low-income housing (existing)				
	Rajasthan	Andhra Pradesh	Karnataka	Uttar Pradesh	Uttarakhand
Fly ash bricks					
Concrete blocks					
Stone filler blocks					
AAC blocks					
Rat-trap bond walls in burnt clay bricks					
Filler slab roof					
Precast brick panel roof					
Precast plank joist roof					
Jack arch roof					
EPS panels for walling and roofing					
GFRC wall and roof					
Monolithic concrete technology					
Natural fiber composite door shutters					
Precast RCC door-window frames					

The next section explores the challenges and gaps in the adoption of energy efficiency measures in the affordable housing sector.

35 Herda et al.

36 Herda et al.

37 Herda et al.

1.4 Adopting energy efficiency in affordable housing – challenges and gaps

India has already taken various initiatives in terms of policies, standards, and green building rating systems to address the rising cooling demand in the country. While these codes and standards are mainstreaming energy efficiency, India still faces significant challenges in improving energy efficiency and environmental performance, the most important being the following:

- For typical low-, mid-, or high-rise affordable residential building construction, the cost is the primary factor considered by the developer, and thus, cooling demand reduction is not prioritised. Therefore, there needs to be more prescriptive information that can be generalised for each affordable housing complex or building, eliminating the dependency on specialised consultancy for this.
- There is a lack of comprehensive information and technical know-how on building design, including templates, energy efficiency measures, equipment and material specifications, and energy-efficient building construction guidelines that the end-user could directly adopt to make the buildings/houses thermally comfortable and energy-efficient.
- Affordable technical solutions are not available on a large scale, leading to high incremental cost when compared to the BAU scenario.
- There is a lack of awareness amongst the masses on the benefits of the energy-efficient construction, along with a lack of structured information and trained resources to implement and construct energy-efficient buildings, making it difficult to convince communities of the need for such construction.
- Financing schemes and additional incentives to fund the construction of thermally comfortable and energy-efficient buildings are not available.

These challenges overshadow the potential benefits that an energy-efficient building offers and discourage management boards, owners, and developers from investing in such buildings. There is a lack of financing schemes for affordable housing that needs to be addressed. However, capital costs are likely to be recovered through different strategies like sourcing local materials and procuring recycled/reused materials. At the same time, the regulatory framework regarding duty relaxation, incentives, and tax benefits needs to be revised. Furthermore, innovative financing schemes are needed to enable developers to consciously work towards energy efficiency. Finally, there need to be awareness campaigns on one or more of the following:

- Reduced energy bills for users, which can serve as a powerful marketing tool
- Shorter payback periods than for a conventional building
- Intangible benefits like contributing to the economy and environment.

Aligning closely with the ENS, ICAP, HPMP, and PMAY initiatives, innovative design strategies and cooling technology alternatives are needed. This will address the challenges related to affordability and climate change, emphasising HCFC phase-out from the affordable housing sector in India and making these buildings thermally comfortable and energy-efficient. The project objective is to take an integrated approach to reducing the cooling load in buildings and advancing the agenda of energy-efficient & environmentally-friendly cooling systems. This can be achieved through climate-appropriate building design, including low-energy cooling technologies and environmentally-friendly refrigerants with low or no global warming potential. Furthermore, building thermally comfortable housing for the lower-income segments is vital for enhancing occupant resilience, public health, and productivity. The project therefore focuses on climate-resilient, efficient, and sustainable thermal comfort solutions for affordable housing.

The objectives of the study are closely aligned with ICAP recommendations while promoting an integrated approach to climate-appropriate building design, including low-energy cooling technologies and environmentally-friendly refrigerants with low or no GWP.

02 ABOUT THE STUDY

2.1 Objectives and goals

Affordable housing is a crucial sub-sector of housing, considering the lack of universal access to housing in the country and ongoing PMAY programme. The affordable housing sector would benefit from using climate-appropriate and energy-efficient building designs to construct houses for the EWS and LIG segments. This, among other approaches, could provide thermal comfort for all, reduce the cooling load, and provide energy efficiency gains. In this regard, the ENS energy-efficient building envelope guidelines could also be enforced in an indirect approach as a byproduct of adopting the guidelines proposed in this report.

Given the project's aim is to implement HPMP-II in the affordable housing sector in India, this study conducted by AEEE focuses on overall reduction in the cooling load and refrigerant requirement. The specific objectives of the study are as follows:

1 Examining the application of non-ODS and low-GWP alternatives in the building sector in India:

   A. Identifying non-ODS and low-GWP alternative refrigerants and technologies for affordable housing

   B. Reducing the cooling demand through replicable building design features for affordable housing

2 Conducting training workshops: two consultation workshops for urban planners, policymakers, building developers, building professionals, and architectural students.

These objectives are closely aligned with ICAP recommendations, while promoting an integrated approach to climate-appropriate building design, including low-energy cooling technologies and environmentally-friendly refrigerants with low or no GWP.

The project aims to implement HPMP-II in the affordable housing sector in India and focuses on overall reduction in the cooling load and refrigerant requirement.

2.2 Scope of work

The following are the main proposed project activities under different work packages:

1. Literature review of existing best practices for design strategies and low cooling refrigerant alternatives

2. Identification of refrigerant and low-energy cooling technology alternatives

3. Evaluation of building design interventions and low-energy cooling technologies for cooling and energy demand reduction

4. Expert stakeholder consultation workshops to mainstream design interventions and low-energy cooling technologies in affordable housing.

The study included collecting, compiling, and analysing information through secondary desk research. However, field visits/measurement-related sub-activities have been replaced by expert stakeholder consultation and secondary research due to the coronavirus disease of 2019 (COVID-19) pandemic. The consultation included a set of questions that enabled the experts to summarise their field experience and assess potential savings from each passive and low-energy cooling system. Conclusions were drawn on building-related HCFC-based application alternatives. The study does not include field measurements or simulations. Expert consultations were meant to fill any potential gaps due to the non-inclusion of site visits and simulations. The experts consulted were sectoral industry stalwarts who have hands-on experience in both of these activities. Additionally, their inputs were also sought regarding the market perception on materials for cost-effective construction and optimal design practices, strengthening this study by making it more practically applicable and relevant to building investors and developers.

The consultation included a set of questions that enabled the experts to summarise their field experience and assess potential savings from each passive and low-energy cooling system.

2.3 Approach and methodology

The study's methodology is depicted in Figure 5. Secondary research, expert stakeholder consultation, and previous team experience were used to identify various passive strategies. A brief impact analysis was internally conducted, after which one-on-one expert stakeholder consultations were scheduled in the case of gaps and consultation requirements. The project team adopted a collaborative and consultative approach to performing the tasks and derived the study outcomes. The study required inputs from multiple sectoral experts working with or for policymakers at the central level, architects, designers, technology experts, developers, and researchers.

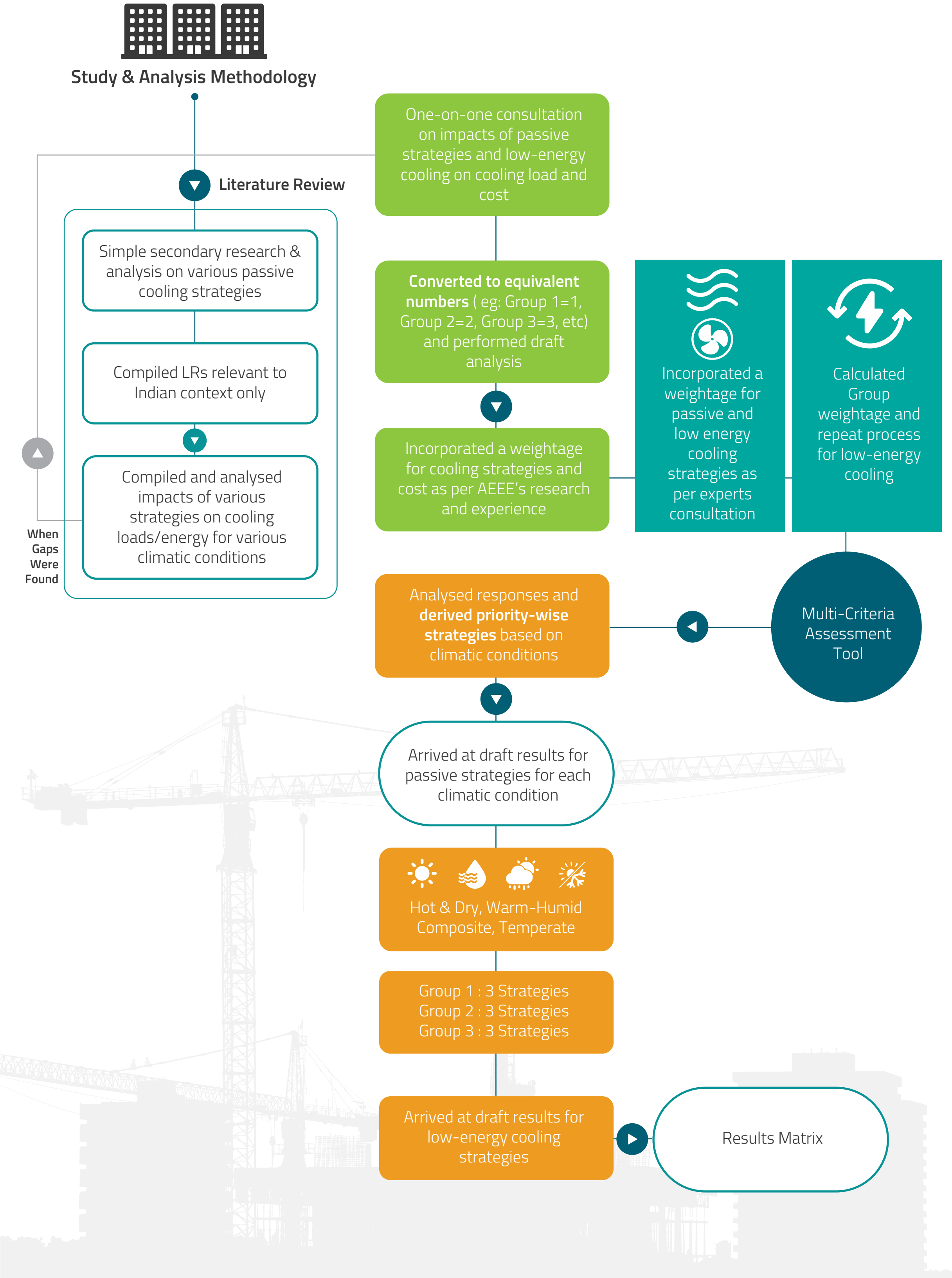
The identified expert consultants were primarily practicing architects, green building consultants, developers, and academicians. Responses were obtained to gain market perspective and insight into industry best practices, and the results were extended to affordable housing recommendations based on a priority ranking.

This study considers two performance parameters: cooling load reduction potential and cost impact. There have been studies on each of these topics individually, but very few on optimising these two together. Building energy professionals and architects with significant knowledge of building science and working on a range of projects across multiple locations were consulted, which is the study's unique feature. The report intends to kickstart building energy efficiency implementation through simple and easy-to-understand recommendations to be incorporated into the design and construction of the conventional new building stock.

Building energy professionals and architects with significant knowledge of building science and working on a range of projects across multiple locations were consulted, which is the study's unique feature.

The responses were collated and converted to equivalent numbers to enable quantitative response-oriented research analysis. The final recommendations were derived from a multi-criteria assessment of passive and low-energy cooling strategies based on cooling load, cost, scalability, and applicability. The recommendations can be linked to ICAP recommendations on the need for thermal comfort for all, energy efficiency in the residential building sector, the need for reduction of RAC-related energy demand, and identification and promotion of not-in-kind (low-energy) cooling technology, including direct and indirect HCFC-based applications.

Figure 5 : Study methodology



Pathway to the adoption of Eco Niwas Samhita

This study has incorporated thresholds from the ENS wherever possible and necessary, as evident from Section 3. It ensures that India, as a country, works towards its mission of 'Housing for all' under PMAY-U and aligns with the ENS to ensure building professionals work towards implementation of efficient RACs. The implementation is in its initial stages now, and this report intends to nudge building sector stakeholders towards adopting the same.

2.4 Limitations of the study

The project scope was limited to developing a general set of guidelines that could help end-users and investors adopt efficient building design and low-energy cooling technologies. Thus, the methodology adopted for this study is based on expert consultations with the aim of developing optimised, energy-efficient, and cost-effective design. It aims to push investors and developers towards adopting optimum energy efficiency strategies based on the uniqueness of the project, using the above-mentioned approach. This methodology and the associated recommendations may not work in all contexts but will still lead to better building design in most cases. This study does not include numerical quantification through building energy simulations, as it is beyond the scope and timeline of this report. Qualitative secondary research, coupled with consultations with expert stakeholders in the industry, is the unique approach of this study, as explained in the previous section. The goal is to facilitate the transition to energy-efficient affordable housing without compromising the main architectural design and implementation.

03 ALTERNATIVES: PASSIVE DESIGN STRATEGIES AND TECHNOLOGY ALTERNATIVES

While passive strategies focus on attaining adaptive thermal comfort to an acceptable degree without additional energy consumption, low-energy cooling strategies can achieve a comparatively higher degree of thermal comfort with minimum additional energy consumption.

To phase out HCFCs and reduce energy consumption, reducing the cooling load in the built environment is essential. Unfortunately, there have been very few case studies on affordable housing incorporating building energy efficiency measures. This chapter presents the key findings from the extensive literature review of low-energy active cooling technologies and low-GWP refrigerant alternatives suitable for affordable housing [38].

There are two different metrics of interest:

A. Cost of design and construction during the initial stages - more relevant to investors than the lifecycle and operational cost savings.

B. Cost of operation, maintenance, and lifecycle - more relevant to the building owners and users.

These costs depend on the energy conservation measures (ECMs) that are being adopted for the building. In the Indian context, ECMs are directed towards cooling, as India is a cooling-dominated country. These ECMs are broadly divided into two categories, as follows:

- Passive cooling strategies
- Low-energy cooling strategies.

Passive and low-energy cooling strategies are more directly relevant to affordable housing within the scope of this study than active cooling strategies. While passive strategies focus on attaining adaptive thermal comfort to an acceptable degree without additional energy consumption, low-energy cooling strategies can achieve a comparatively higher degree of thermal comfort with minimum additional energy consumption.

38 Ashok B Lall Architects, "Low Carbon Resource- Efficient Affordable Housing," no. July (2017).

This additional energy consumption is comparatively much lower than that of conventional air conditioning systems with active cooling strategies. All these strategies aim to address cooling demand either directly or indirectly. While passive strategies primarily focus on reducing building cooling loads through heat avoidance and reduction, low-energy and active cooling systems focus on addressing the cooling demand resulting from the load on the building. For this study, we consider only passive and low-energy cooling strategies.

3.1 Cooling load reduction through passive strategies

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 numerous factors, such as the following:

- **Climatic conditions** - ambient temperatures, relative humidity, & air velocity: Analysing these parameters contributes to the evaluation of various passive and low-energy cooling strategies' feasibility.
- **Sun path and orientation:** Studying the sun path aids in determining the optimal building orientation, fixing the window-to-wall ratio (WWR), and designing shading devices.
- **Wind direction and wind temperature:** Analysing these aspects can help in optimising the building orientation and WWR based on wind direction, in conjuncture with the sun path.
- **Ground temperatures**: Understanding ambient conditions and ground temperature conditions facilitates the identification of heat sink locations and assessment of the feasibility of low-energy cooling strategies like geothermal or ground cooling.
- **Sky/cloud cover**: Evaluating and understanding sky conditions and cloud cover can help decode ambient conditions in a given location and estimate the global horizontal radiation potential. The latter is a measure of the direct radiation component's intensity on the various facades of a building.

Although design recommendations can be standardised to a certain extent, the abovementioned factors need to be studied cautiously on a case-by-case basis. The categorisation of various strategies is summarised in Table 7 and further discussed in the subsections below.

Although design recommendations can be standardised to a certain extent, the climate-dependent factors need to be studied cautiously on a case-by-case basis.

Table 7 : Strategies to reduce energy consumption and improve thermal comfort[39]

Cooling strategy type	Cooling mode (or cooling through)	Strategy level	Strategies
Passive cooling strategies	Radiation	Building design strategies	Orientation
			WWR
			Building shading
	Conduction	Envelope strategies	Wall assembly and properties
			Roof assembly and properties
			Glazing assembly and properties
	Convection	Natural ventilation strategies	Natural cross ventilation
			Night flush ventilation
Low-energy cooling technologies	Mix/any	Cooling technologies	Super-efficient fans
			Evaporative air coolers

Note: The tables in this section incorporate thresholds from ECBC-2017 and ENS 2018 where needed. The performance parameters' thresholds for these are based on ECBC 2017 (rather than ECBC+ or ECBC Super) to address the 'affordability' part of affordable housing. This report has been developed based on metrics that matter and are readily perceivable to encourage a higher compliance rate from potential stakeholders and developers, who will play an integral role in implementing affordable housing.

Passive cooling strategies[40][41][42][43][44] are design interventions applied to buildings to control heat transfer into the building, thereby reducing cooling loads without increasing energy costs. Figure 6 below illustrates the heat transfer modes that need to be passively addressed in any building. The categorisation divides passive strategies based on the mode of cooling, as per the following:

1. Radiation
2. Conduction
3. Convection

39 Norbert Lechner, Heating, Cooling, Lighting, 4th ed. (New Jersey: Wiley, 2015).

40 Nick Barnard et al., "IEA Annex 28, Low Energy Cooling. Technology Selection and Early Design Guidance," 2001, 98.

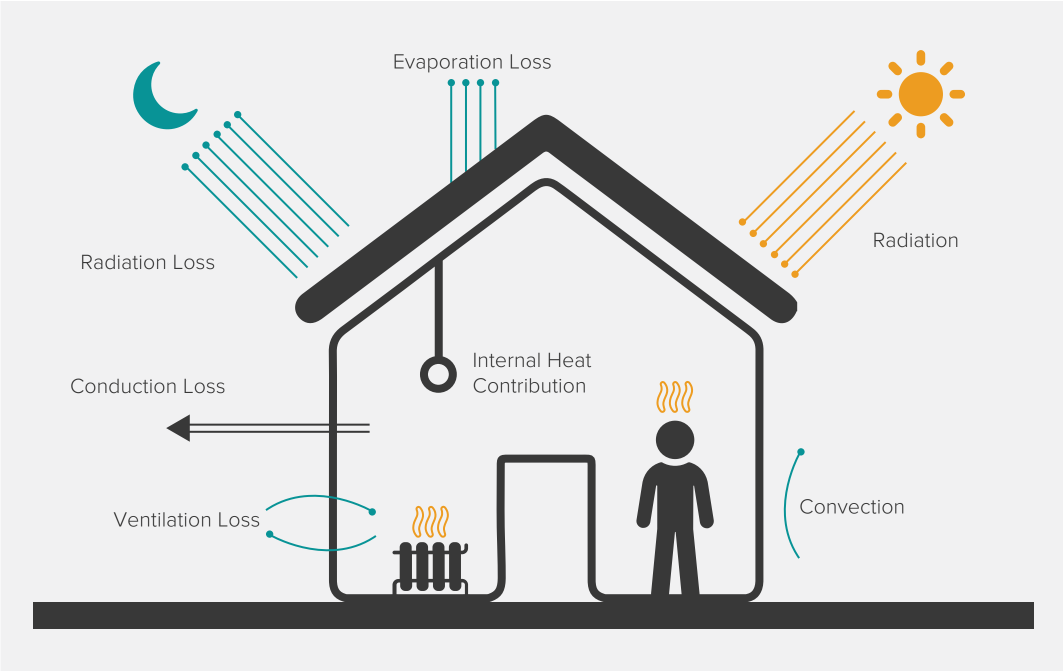
41B. Givoni, "Performance and Applicability of Passive and Low-Energy Cooling Systems," Energy and Buildings 17, no. 3 (1991): 177–99, https://doi.org/10.1016/0378-7788(91)90106-D.

42 Karthik Panchabikesan, Kumaresan Vellaisamy, and Velraj Ramalingam, "Passive Cooling Potential in Buildings under Various Climatic Conditions in India," Renewable and Sustainable Energy Reviews 78, no. March (2017): 1236–52, https://doi.org/10.1016/j.rser.2017.05.030.

43 Norbert Lechner, Heating, Cooling, Lighting: Sustainable Design Methods for Architects, n.d.

44 Hanan M. Taleb, "Using Passive Cooling Strategies to Improve Thermal Performance and Reduce Energy Consumption of Residential Buildings in U.A.E. Buildings," Frontiers of Architectural Research 3, no. 2 (2014): 154–65, https://doi.org/10.1016/j.foar.2014.01.002.

Figure 6 : Heat transfer through radiation, conduction, & convection

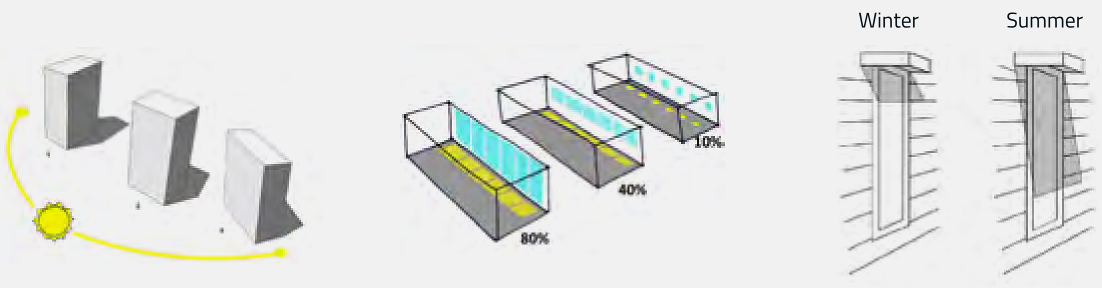


The strategies tackling the different heat transfer modes are briefly discussed in the following subsections. The decision-making process for an investor/developer is elaborated, along with best practices for each strategy. It should be noted that these best practices are indicative and function as initial information to help direct the investor towards energy efficiency interventions.

3.1.1 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, optimising the façade's WWR, and designing shading devices—dependent on the radiation component of heat are together termed the 'building design strategies', depicted in Figure 7 below

Figure 7 : Optimising heat transfer through radiation[45] [46]. (orientation, WWR, shading)



7a
Source: Theconstructor.org

7b
Source: Fairconditioning.org

7c
Source: Researchgate.net

45 "Design Options | Revit Products 2018 | Autodesk Knowledge Network," n.d.

46 "Concrete Brasilia," n.d.

A. Orientation

Orienting the longer axis of a building based on the solar altitude and azimuth angles to prevent exposure of the longer facade to direct radiation is one of the crucial initial design decisions. The orientation of a building is selected based on the solar path, altitude angles, azimuth angles, cloud cover, global horizontal radiation, prevailing wind direction, and temperature of incoming wind [47 48 49 50]. Table 8 below explains the applicability of orientation in the context of buildings and affordable housing.

The orientation of a building is selected based on the solar path, altitude angles, azimuth angles, cloud cover, global horizontal radiation, prevailing wind direction, and temperature of incoming wind

Table 8 : Applicability of orientation strategy to affordable housing

Decision-making process	Best practices and applicable thresholds
■ India, being in the northern hemisphere, receives most of its direct radiation from the southern direction. This is evident from the sun path from 36°N to 8°N. ■ Depending on the ambient climatic conditions (hot or cold), it has to be decided whether the building needs to be passively cooled or heated. However, the Indian context primarily requires cooling. The building orientation needs to be fixed accordingly. ■ The sun angles—altitude, azimuth, and intensity of direct/diffused horizontal radiation—need to be studied to understand peak climatic conditions. ■ Wind direction also needs to be studied to decide on placing windows in angles between cardinal directions (e.g. S-W or N-E instead of S or N). ■ Various orientations (like +5°, +15°, etc.) can be studied through simple shoebox analyses, in order to determine the optimal orientation.	■ For passive cooling, orient the building along the N-S axis. ■ For passive heating, orient the building along the E-W axis. ■ Weightage to be given more to wind direction to enhance natural ventilation in warm-humid, composite, and temperate climates. Additionally, the design needs to ensure that the floor plates are thin and not too deep. It is also important to incorporate natural ventilation and wind direction when applying these best practices. This is applicable for all climates in India except cold climates.[51 52]

47 Rania E. Ashmawy and Neveen Y. Azmy, "Buildings Orientation and Its Impact on the Energy Consumption," The Academic Research Community Publication 2, no. 3 (2018): 35, https://doi.org/10.21625/archive.v2i3.344.

48 Siddhartha and Maya Yeshwanth Pai, "Effect of Building Orientation and Window Glazing on the Energy Consumption of HVAC System of an Office Building for Different Climate Zones," International Journal of Engineering Research & Technology 4, no. 09 (2015): 838–43, https://doi.org/10.17577/ijertv4is090754.

49 Shakila Pathirana, Asanka Rodrigo, and Rangika Halwatura, "Effect of Building Shape, Orientation, Window to Wall Ratios and Zones on Energy Efficiency and Thermal Comfort of Naturally Ventilated Houses in Tropical Climate," International Journal of Energy and Environmental Engineering 10, no. 1 (2019): 107–20, https://doi.org/10.1007/s40095-018-0295-3.

50 Nikhil V Deshmukh and Yogesh P Kherde, "Case Study on Building Orientation," International Journal of Science and Research (IJSR) 5, no. 3 (2016): 1596–98, https://doi.org/10.21275/v5i3.nov162285.

51 Steven V Szokolay, Introduction to Architectural Science, Elsevier (Oxford, 2004), https://doi.org/10.4324/9780203449110-5.

52 Lechner, Heating, Cooling, Lighting.

B. Window-to-wall ratio

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 [53] [54] [55] [56]. Table 9 below explains the applicability of WWR to affordable housing.

Table 9 : Applicability of WWR strategy to affordable housing

Decision-making process	Best practices and applicable thresholds
■ The WWR should ideally be optimised after the orientation of the building is optimised. ■ The sun angles—altitude, azimuth, and intensity of direct/diffused horizontal radiation—need to be studied to analyse the placement of windows in various facades of the building. The placement needs to be mainly decided based on the intensity of direct radiation during peak summer months. ■ The WWR needs to be optimised for heat and daylight. The window-to-floor area ratio (WFR) has to be considered for this; more specifically, it has to be studied to understand daylight availability. ■ Various WWRs can be assessed through simple shoebox analyses (using a simple rectangular building with two thermal zones—perimeter and core—to perform multiple exploratory parametric analyses), and, in this way, the optimal WWR can be determined. ■ This is not a standalone decision and always has to be optimised with 'shading' as another passive strategy and the window size required for natural ventilation. Optimising the WWR, along with ensuring appropriate shading, is considered a best practice.	■ 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. In addition to this, the selection of the frame material and its assembly also contribute to heat gain. Assembling should be cautiously done to avoid thermal bridging from the exterior portion to the interior. This is applicable for all climates in India except cold climates.[57] [58] Apart from this, to optimise heat and daylight, the ENS 2018 recommends the following minimum visible light transmittance (VLT) for different WWR:

WWR	VLT
0-30%	0.27
31-40%	0.20
41-50%	0.16
51-60%	0.13
61-70%	0.11

53 Pathirana, Rodrigo, and Halwatura, "Effect of Building Shape, Orientation, Window to Wall Ratios and Zones on Energy Efficiency and Thermal Comfort of Naturally Ventilated Houses in Tropical Climate."

54 Bureau of Energy Efficiency, Ministry of Power, Government of India, Eco-Niwas Samhita 2018 (ECBC-R) Part 1: Building Envelope, Ministry of Power, Government of India, Vol. 1, 2018.

55 Srijan Didwania, Vishal Garg, and Jyotirmay Mathur, "Optimization of Window-Wall Ratio for Different Building Types," Research Gate, no. January (2011).

56 Nima Izadyar et al., "Impacts of Façade Openings' Geometry on Natural Ventilation and Occupants' Perception: A Review," Building and Environment 170 (2020): 106613, https://doi.org/10.1016/j.buildenv.2019.106613.

57 Lechner, Heating, Cooling, Lighting.

58 Szokolay, Introduction to Architectural Science, 2004.

C. 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 [59 60 61]. Table 10 below summarises the applicability of shading to affordable housing.

The WWR needs to be optimised for heat and daylight. The window-to-floor area ratio (WFR) has to be considered for this; more specifically, it has to be studied to understand daylight.

Table 10 : Applicability of window shading strategy to affordable housing

Decision-making process	Best practices and applicable thresholds
■ Window shading does not always have to be designed such that the shading device shades the entire window throughout the year. This can lead to unnecessary cooling during the winter months and deep overhangs or fins that may not be feasible, considering practical onsite scenarios.	South façade - horizontal overhangs East and west façades - horizontal + vertical fins (preferred) North façade – horizontal overhangs (if needed for resistance to rain and weather-proofing)
■ Based on the peak summer months and intensities, the peak altitude and azimuth angles can be derived. Shading devices can be designed to shade the buildings during such energy-intensive months/seasons, resulting in cost and energy savings.	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. Furthermore, operable shading devices result in occupant satisfaction and comfort due to control being given to the occupants. This is applicable for all climates in India except cold climates.

3.1.2 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, as depicted below in Figure 8).

Figure 8 : Optimising heat transfer through conduction62 63 (walls, window glazing, roof)

8a Source: NCMA.org

8b Source: Bestpickreports.com

8c Source: Technical Guide Roof Board

59 Steven Szokolay, "Introduction to Architectural Science," Geopolitical Traditions, 2020, 17–40, https://doi.org/10.4324/9780203449110-5.

60 Pierre Jaboyedoff et al., "Energy Efficient Building Envelope & Ventilation Strategies for Multi-Storey Residential Buildings in India," 2014, 53–61.

61 Lechner, Heating, Cooling, Lighting: Sustainable Design Methods for Architects.

62 "Insulating Concrete Masonry Walls, NCMA," n.d.

63 "How to Choose the Best Window Glass | Best Pick Reports," n.d.

The term 'envelope' refers to all the exterior building components, including the walls, roof, and glazing. Energy reduction in the building envelope is one of the main strategies needed to address loads in a building. This subsection breaks down the abovementioned envelope components and highlights best practices and the applicability to affordable housing.

A. Wall assembly and properties

The specifications and properties of the wall materials that constitute the assembly govern the effectiveness of heat conduction by the wall. The properties of individual wall materials like the conductivity, specific density, specific heat, and thickness assist in calculating the assembly's conductance. Table 11 summarises the applicability of envelope strategies for walls to affordable housing [64] [65].

Table 11 : Applicability of envelope strategies - wall assemblies - to affordable housing

Decision-making process	Best practices and applicable thresholds	
■ The climate of the location needs to be studied initially. ■ Materials and material assemblies and their availability in various locations must be determined, and insulation must be selected accordingly. ■ For the Indian scenario, insulation is suitable for warm-humid, hot and dry, and composite climates. ■ It is essential to use insulation that does not use HCFCs as foam blowing agents. Alternatives for the same have already been discussed in previous sections.	Composite	U-value = 0.4 W/m²K
	Warm-humid	U-value = 0.4 W/m²K
	Hot & dry	U-value = 0.4 W/m²K
	Temperate	U-value = 0.55 W/m²K

Precautionary construction measures: For construction and laying of walls, precautions need to be taken to ensure tightly-sealed envelope and joints, water proofing and resistance, sill and lintel level joinery to prevent thermal bridging, and good workmanship.

B. Window glazing assembly and properties:

'Window glazing' here refers to the glass pane/panes that constitute the window. In cases where more than one glass pane (2 or 3) are installed with air cavities between them, this is called double or triple glazing. The performance metrics governing these glazing units include the solar heat gain coefficient (SHGC), U-value, and VLT. Apart from these, recent technologies like low-E coatings have also started influencing heat transfer through glazing. Low-E coatings are microscopically thin, shiny metallic coatings applied on a glass surface to decrease its emissivity. Another practical technological advancement is spectrally selective low-E coatings, which transmit visible radiation through the glazing, but not infrared radiation, and hence have a high VLT but low SHGC and U-value. Windows and glazing are the thermally weakest areas in a building envelope.

64 Bureau of Energy Efficiency, "ECBC 2017," 2017.

65 Kumar, S., Singh, M., Chandiwala, S., Sneha, S., & George, "Mainstreaming Thermal Comfort for All and Resource Efficiency in Affordable Housing."

Therefore, effective and correct decision-making regarding these components is critical. Table 12 below summarises the applicability of envelope strategies for window glazing in the context of affordable housing[66] [67] [68].

Table 12 : Applicability of envelope strategies - window glazing - to affordable housing

Decision-making process	Best practices and applicable thresholds	
■ The WWR should ideally be determined before selecting the glazing and glazing parameters. ■ Oversizing or undersizing of windows may lead to excessive heat gain during the day or excessive heat loss at night.	Composite	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)
	Warm-humid	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)
	Hot & dry	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)
	Temperate	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)

Precautionary construction measures: In window installation, precautions must be taken to ensure ideal material selection for window frames and windows, minimal thermal bridging components, and tightly-sealed installation of glazing assembly to prevent infiltration from the exterior and exfiltration from the interior.

C. Roof assembly and properties

Hardscapes in a roof contribute to high heat gain, which is eventually conducted through the roof assembly. The performance metrics for selecting the appropriate materials and assembly include the U-value, surface reflectance, emissivity, and solar reflectance index (SRI).

66 Bureau of Energy Efficiency, "ECBC 2017."

67 Marian Keeler and Prasad Vaidya, Fundamentals of Integrated Design for Sustainable Building, 2nd ed. (New Jersey: Wiley, 2016).

68 G. Kiran Kumar, S. Saboor, and T. P. Ashok Babu, "Experimental and Theoretical Studies of Window Glazing Materials of Green Energy Building in Indian Climatic Zones," Energy Procedia 109, no. November 2016 (2017): 306–13, https://doi.org/10.1016/j.egypro.2017.03.072.

Roofing materials with high SRI values are termed 'cool roofs.' Cool roofs have gained popularity over the past decade and are easy to implement. Vegetated roofs and green roofs can also reduce cooling loads and become part of cool roofs. Apart from these, there are many efficient roofing methods, such as concrete roofs, insulated roofs, roof gardens, solar photovoltaic roofs, bisolar roofs, double-skin roofs, and roof ponds[69 70 71]. Table 13 below explains the applicability of envelope strategies for roofs to affordable housing.

Table 13 : Applicability of envelope strategies - roofs - to affordable housing

Decision-making process	Best practices and applicable thresholds	
■ Selection of materials and assembly for roofs can be made in conjuncture with that of walls.	Composite	U-value = 0.33 W/m²K
■ Moreover, cool roofs can be implemented in almost any location and are a cost-effective strategy that can lead to a significant reduction in the cooling load.	Warm-humid	U-value = 0.33 W/m²K
■ It can be incorporated as a less expensive strategy in existing buildings, in addition to new installations.	Hot & dry	U-value = 0.33 W/m²K
	Temperate	U-value = 0.33 W/m²K

Precautionary construction measures: For construction and roof laying, precautions need to be taken to ensure the ideal slope, waterproofing, and surface treatment of the roof, rainwater runoff features, and good workmanship.

D. Residential envelope transmittance value

The residential envelope transmittance value (RETV) is the net heat gain rate through the building envelope, excluding the roof. RETV is not a strategy, but rather an approach to calculating the heat gains resulting from all of the abovementioned building components[72].

RETV is calculated as follows:

$$RETV = \frac{1}{A_{envelope}} \times \begin{bmatrix} \left\{ a \times \sum_{i=1}^{n} \left(A_{opaque_i} \times U_{opaque_i} \times \omega_i \right) \right\} \\ + \left\{ b \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times U_{non-opaque_i} \times \omega_i \right) \right\} \\ + \left\{ c \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times SHGC_{eq_i} \times \omega_i \right) \right\} \end{bmatrix}$$

69 Bureau of Energy Efficiency, "ECBC 2017."

70 Keeler and Vaidya, Fundamentals of Integrated Design for Sustainable Building.

71 Majed Abuseif and Zhonghua Gou, "A Review of Roofing Methods: Construction Features, Heat Reduction, Payback Period and Climatic Responsiveness," Energies 11, no. 11 (2018), https://doi.org/10.3390/en11113196.

72 Bureau of Energy Efficiency, Eco-Niwas Samhita.

where

$A_{envelope}$	:	envelope area (excluding roof) of dwelling units (m²). It is the gross external wall area (includes the area of the walls and the openings such as windows and doors).
A_{opaque_i}	:	areas of different opaque building envelope components (m²)
U_{opaque_i}	:	thermal transmittance values of different opaque building envelope components (W/m².K)
$A_{non\text{-}opaque_i}$	:	areas of different non-opaque building envelope components (m²)
$U_{non\text{-}opaque_i}$	:	thermal transmittance values of different non-opaque building envelope components (W/m².K)
$SHGC_{eq_i}$	:	equivalent solar heat gain coefficient values of different non-opaque building envelope components
ω_i	:	orientation factor of respective opaque and non-opaque building envelope components; it is a measure of the amount of direct and diffused solar radiation that is received on the vertical surface in a specific orientation

Limiting the RETV value contributes to reducing heat gains from the envelope. The ENS recommends a maximum RETV of 15 W/m² (excluding the roof component) for all climates. The coefficients used to calculate the RETV vary based on the climate; Table 14 specifies these different coefficients. If individual envelope component specifications are yet to be finalised in a design, the RETV calculation can be effective in the selection of envelope materials as it gives a quantitative measure of heat gains through the building envelope (except roof). Design decisions can be made based on whether the RETV value is greater or lesser than 15W/m².

Table 14 : RETV coefficients[73]

Climate	a	b	c
Composite	6.06	1.85	68.99
Hot & dry	6.06	1.85	68.99
Warm-humid	5.15	1.31	65.21
Temperate	3.38	0.37	63.69

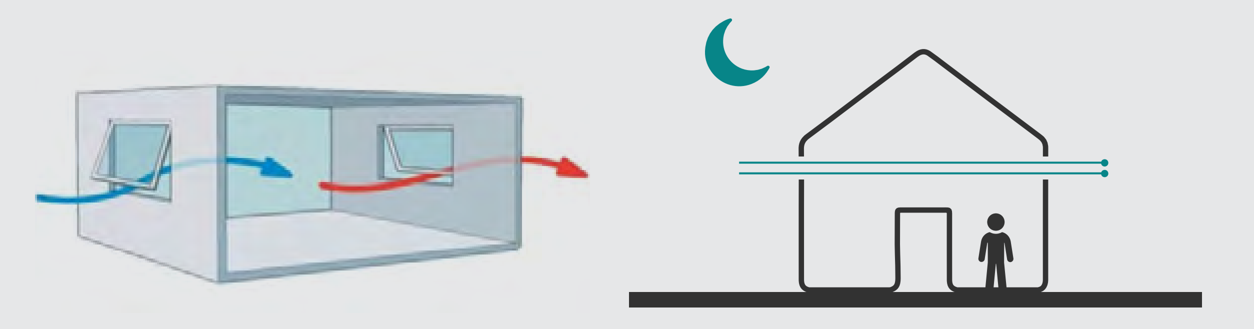
3.1.3 Convection

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, such as cross ventilation, stack ventilation, wind towers, ventilation through atria, night flush ventilation etc . However, considering the various complexities and implementation logistics, we will limit our scope to cross ventilation and night flush ventilation in this context as depicted in Figure 9.

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, such as cross ventilation, stack ventilation, wind towers, ventilation through atria, night flush ventilation etc .

73 Bureau of Energy Efficiency, Ministry of Power, Government of India, Eco-Niwas Samhita 2018 (ECBC-R) Part 1: Building Envelope.

Figure 9 : Optimising heat transfer through convection



A. Natural cross ventilation

The movement and cross flow of air between one side of the building and another is called 'cross ventilation.' The Air Changes per Hour (ACH) keeps varying in this natural cooling mode based on micro-atmospheric conditions. The challenge in natural ventilation is that the airflow rate can be high in certain places and low in other places, leading to imbalance and asymmetrical cooling demand in various spots.

B. 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 optimised orientation enhances the effect of night flush ventilation. Table 15 below explains the applicability of natural ventilation strategies to affordable housing.

Table 15 : Applicability of natural ventilation strategies to affordable housing

Decision-making process	Best practices and applicable thresholds	
■ The wind direction needs to be analysed, and the ventilation strategy optimised accordingly based on orientation and natural ventilation mechanisms. ■ 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.	Composite	Min WFR = 12.5%
	Warm-humid	Min WFR = 16.6%
	Hot & dry	Min WFR = 10.0 %
	Temperate	Min WFR = 12.5%
	Common	Fewer deep floor plates, in order for night flush ventilation to be effective, are recommended.

In addition to the identified design alternatives, several alternative low-energy cooling strategies have been identified to drive the agenda of energy-efficient and environment-friendly cooling solutions.

Landscape & vegetation, water bodies, and mutual shading from adjacent buildings can also indirectly reduce the cooling load.

3.1. 4 Micro-climatic components

In addition to the conduction, convection, and radiation components of heat that can be addressed to reduce a building's cooling load, other environmental factors like landscape & vegetation, water bodies, and mutual shading from adjacent buildings can also indirectly reduce the cooling load. These factors contribute to enhancing thermal comfort through micro-climatic impact. Sites with multiple buildings can be designed to incorporate mutual shading of two buildings to reduce their cooling loads and provide enhanced thermal comfort thanks to the shading effect. Vegetation and landscape components like trees, shrubs, and planters also help make the micro-climate more conducive to human habitations. These vegetation components reduce air and surface temperatures through shade and evapotranspiration. Shaded materials/surfaces have 11-25 degrees Celsius (°C) lower temperatures than peak surface temperatures of the same material when unshaded. Evapotranspiration has the potential to reduce peak summer temperatures by 1-5°C[74]. Shading can lead to an air temperature reductions of 2.5- 4.5°C indoors, and shading due to vegetation can lead to an air temperature reduction of approximately 5°C[75]. The selection of trees and vegetation, their location, and their growth habits play an essential role in designing an affordable housing complex. Water bodies in predominantly dry climates can also add cooling and necessary humidity to the environment. However, other factors like water availability in the region and maintenance issues need to be considered in the decision-making process.

3.2 Cooling Load reduction through low-energy cooling technologies

Active cooling systems such as RACs significantly contribute to energy and refrigerant demand, leading to increased GHGs. In addition, increasing temperatures have made achieving thermal comfort a basic necessity in existing households. However, purchasing RACs might not be possible for everyone, due to their relatively high cost and usage of HCFC refrigerants. ICAP predicts that even in the next two decades, a significant percentage of households will still not be able to afford air conditioning, due to the higher initial investment for an RAC and the overall lifetime operating costs, i.e. energy bills. In addition to affordability issues, RACs also contribute to an increase in refrigerant use. Thus, there is a need to identify and deploy low-energy cooling strategies that are affordable, refrigerant-free, and integrated into India's affordable housing[76 77].

Low-energy cooling technologies use power-based equipment to provide cooling and thermal comfort .

Low-energy cooling technologies use power-based equipment to provide cooling and thermal comfort. These technologies usually use a heat sink such as a sump, a water tank, and an energy-consuming component such as a fan, blower, pump, or a combination of these to achieve enhanced heat transfer in a particular setting within the building. These low-energy cooling technologies are selected based on their refrigerant usage (low or no GWP and ODS) and applicability in affordable

74 United States Environmental Protection Agency, "Using Trees and Vegetation to Reduce Heat Islands | Heat Island Effect | US EPA," 2019.

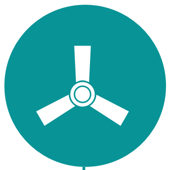
75 Mohammad Arif Kamal, "Shading: A Simple Technique For Passive Cooling And Energy Conservation In Buildings," Sustainable Environment, no. January (2011): 6.

76 Lechner, Heating, Cooling, Lighting: Sustainable Design Methods for Architects.

77 Taleb, "Using Passive Cooling Strategies to Improve Thermal Performance and Reduce Energy Consumption of Residential Buildings in U.A.E. Buildings."

housing units or complexes. There are numerous low-energy cooling strategies. However, this study selected three strategies based on applicability, affordability, scalability, and market potential. The main challenge with such technologies is that, while adaptive thermal comfort is possible, meeting stipulated standards like those of the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) may not be entirely possible[78 79]. The following section reviews existing literature, covering the following aspects:

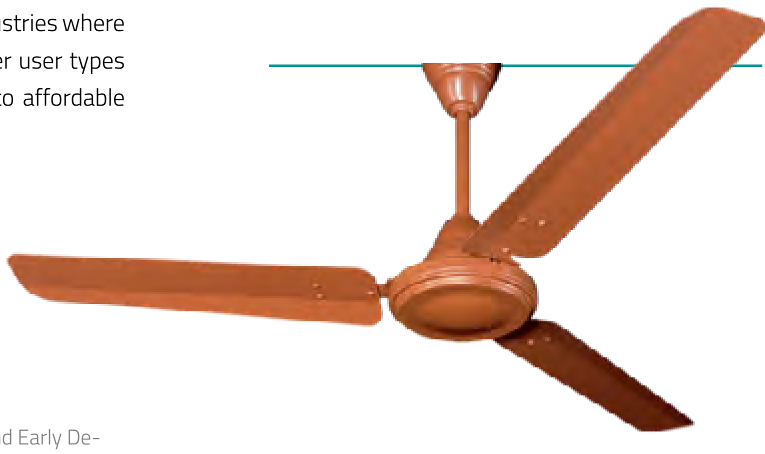
- ➔ A brief description of the technology and its working principle to understand its relevance for affordable housing.
- ➔ The decision-making process leading to the selection of a particular technology.
- ➔ The benefits of using a particular technology.



3.2.1 Super-efficient fans for comfort ventilation

Super-efficient fans have become a widely-accepted energy-efficient appliance in recent years. These can reduce energy consumption by over 40-50% compared to conventional appliances. The brushless direct current (BLDC) fans are currently the most widely used super-efficient fans technology in India. 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. The working of a BLDC is based on the simple interaction of forces between a permanent magnet and an electromagnet. An electronic drive with a sensor is used to constantly change the polarity of the stator to ensure continuous rotor rotation and maintain the BLDC motor's torque. Hence, in a BLDC fan, attraction between the opposite poles and repulsion between the like poles of the rotor and stator inside the BLDC motor results in continuous movement of the rotor due to a constant push & pull mechanism between the rotor and stator, leading to rotation of the BLDC motor. A conventional fan on the other hand differs from a BLDC fan mainly in its commutation method. The technique of changing the current direction in the motor for rotational movement and the use of electromagnets are the main working principle differences between conventional and BLDC fans. The usage of BLDC fans began to be widely used in industries where high torque motors were required and has slowly penetrated to other user types now. Table 16 summarises the applicability of super-efficient fans to affordable housing[80 81 82].

The working of a BLDC is based on the simple interaction of forces between a permanent magnet and an electromagnet.



78 Barnard et al., "IEA Annex 28, Low Energy Cooling. Technology Selection and Early Design Guidance."

79 Givoni, "Performance and Applicability of Passive and Low-Energy Cooling Systems."

80 P.C. Sahid et al., "Energy Efficient Ceiling Fan Using BLDC Motor," International Journal of Engineering Research & Technology vol. 4, no. 04 (2015): 460–64, https://doi.org/10.17577/ijertv4is040600.

81 Bijlibachao Ceiling Fans, "Super Efficient Ceiling Fans in India – Market Analysis : Bijli Bachao," n.d.

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

Table 16 : Applicability of super-efficient fans to affordable housing

Decision-making process	Benefits of technology and relevance to affordable housing
■ Installing super-efficient fans like BLDC fans instead of conventional ceiling fans reduces energy consumption, rather than thermal comfort. ■ Although energy consumption is reduced by over 60% through the use of BLDC fans, the capital cost is almost twice that of a conventional fan. However, the payback period is less than two years in many cases, resulting in a reduced cost of ownership over the product lifecycle. ■ At the same time, BLDC fans are new to the market, with limited awareness amongst consumers about their benefits.	■ A majority of households—almost 93% of Indian families—use ceiling fans to achieve thermal comfort[83]. ■ For affordable housing, a BLDC fan is a better choice than a conventional fan. It contains a BLDC motor with a longer lifespan and is more reliable than a traditional fan motor. The brushes of a brushed direct current (DC) motor wear out over time and eventually necessitate motor rewinding. In a BLDC motor, due to less heat generation, the lifespan of the bearings increases, reducing the risk of short-circuiting, which, in turn, reduces the lifecycle cost of the device. A BLDC fan motor is also lighter and less noisy than a conventional fan motor.

3.2.2 Evaporative air 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. To reduce water consumption, the construction materials of the cooling system needs to be corrosion resistant to a good level to tolerate a high concentration level of dissolved impurities. Additionally, blow-down systems that are load-dependent and fitted with conductivity control can be used. They work well in India's two major climatic zones, i.e. hot-dry and composite; however, their performance decreases in areas with high latent load.

There are three basic types of evaporative air coolers[84] [85] [86] [87] [88]:

1. Direct evaporative air coolers (DECs)

Evaporative coolers work on the simple principle of evaporation and the use of water as a refrigerant.

In DECs, cooling pads are used as the heatsink and add humidity to the air, resulting in cooling. They are best suited for the residential sector and can be applied mainly in hot-dry climates (with RH<40%) due to an increase in relative humidity when cooled. Natural ventilation is more applicable and feasible in residential buildings than non-residential buildings due to growing issues like dust, wind gusts, mosquitoes, and insects that can affect employees/ laborers/users' work and productivity in non-residential buildings.

83 Shalu Agrawal et al., "Awareness and Adoption of Energy Efficiency in Indian Homes: Insights from the India Residential Energy Survey (IRES) 2020," 2020.

84 Barnard et al., "IEA Annex 28, Low Energy Cooling. Technology Selection and Early Design Guidance."

85 O. Amer, R. Boukhanouf, and H. G. Ibrahim, "A Review of Evaporative Cooling Technologies," International Journal of Environmental Science and Development 6, no. 2 (2015): 111–17, https://doi.org/10.7763/ijesd.2015.v6.571.

86 Jesse Dean and Ian Metzger, "Multistaged Indirect Evaporative Cooler Evaluation," no. February (2014): 1–38.

87 Panchabikesan, Vellaisamy, and Ramalingam, "Passive Cooling Potential in Buildings under Various Climatic Conditions in India."

88 Srishti Sharma, Akhil Singhal, and Tarun Garg, "Decoding Evaporative Air Coolers" (New Delhi, June 2021).

2. Indirect evaporative air coolers (IECs)

IECs use a heat exchanger as their 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 conditions.

3. Indirect-direct evaporative air coolers (IDECs)

IDECs are also known as two-stage evaporative air coolers. The technology combines an IEC 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. This type is best-suited for low-rise or mid-rise (LIG and MIG) building designs and the commercial & industrial sector. It is applicable to composite/hot & dry climatic zones. Table 17 summarises evaporative air coolers' applicability to the affordable housing sector.

Table 17 : Applicability of evaporative air coolers to affordable housing

Decision-making process	Benefits of technology and relevance to affordable housing
■ The climatic parameters need to be considered. In addition, 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 have high sensible and low latent loads and require addition of humidity. IECs work best in areas that have high sensible and latent loads and does not usually change the humidity of the cooled air inside. IDECs also work best in areas that have high sensible and latent loads but increases the humidity of the cooled air inside, unlike IECs. ■ Different types of evaporative cooling systems are recommended for different climates, as mentioned above.	■ Evaporative air coolers are an appropriate fit for affordable housing, being a more economical technology with easy self-operation & maintenance. ■ The technology is readily available and is a sustainable alternative to energy-intensive refrigerant-based space cooling technologies such as RACs.

3.3 Summary of passive design and low-energy cooling technologies

Table 18 summarises the main passive design and low-energy cooling technologies for affordable housing. Each strategy has different applicability in various climates, and their impacts in terms of reducing energy consumption also vary. This table has been prepared based on a literature review on HPMP-II and ENS, work done by AEEE under the Solar Decathlon India (SDI)[89], and the AEEE team's previous experience in various affordable housing projects.

It should be noted that the recommendations given in this table consider commonly available and accessible building materials as per the ENS, which focuses on high-performance materials. These recommendations were then used as the basis for expert stakeholder meetings, further detailed in the following sections.

89 Solar Decathlon India, "Solar Decathalon India _ Join the Challange _ Competition _ Home," n.d.

Table 18 : Literature-based recommendations on passive strategies

Sl.No	Passive strategies	General Recommendation under passive strategy based on literature reviews
1	Orientation	N-S predominantly
		NW-SE - option-2
2	WWR	<30%
3	Window Shading	South- horizontal
		East & west- vertical
		North- optional
4	Glazing type (select)	Single glazing - E, W, N
		Double glazing- south only
5	Ventilation- cross and night flush	Openings on 2 sides of room with WWR<30% each with min. WFR
6	Ventilators	2' high ventilators above 7' in habitable areas
7	Wall materials	Below are commonly available materials in India as per ENS
		Solid burnt clay brick
		Hollow brick
		Flyash brick
		Solid concrete block
		AAC block
		CSEB
		RCC
		Lime concrete
		Cellular concrete
8	Envelope insulation	Below are commonly available materials in India without HCFCs
		Note that some insulation materials like PU, Extruded Polystyrene, Phenolic foam, Polyethylene use HCFC during their manufacturing as blowing agents.
		Fiberglass
		Mineral wool
		Cellulose
9	Roof materials & techniques	Below are commonly available materials in India as per ENS
		Brick tile
		Lime concrete
		Mud Phuska
		AC sheet
Sl.No	**Low energy cooling technologies**	**General Recommendation under passive strategy based on literature reviews**
1	Super-efficient 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. Direct evaporative cooling can be used for hot-dry and composite climates. Indirect evaporative cooling can be used for warm-humid and composite climate

04 EXPERT STAKEHOLDER CONSULTATION

Building on the broad recommendations from the literature review, expert stakeholder consultations were carried out to obtain the market perspective on different cooling approaches' and technologies' feasibility, scalability, and affordability. The questionnaire used is attached in Annexure-II. Since most recommendations for buildings in general apply to affordable housing as well, the differentiating parameter is mainly the optimisation between performance and cost. Although this is a significant criterion for any building design focused on energy efficiency, it plays an even more important role in affordable housing; affordability needs to be ensured in all aspects as the primary concern. Enhancing energy efficiency and thermal comfort has therefore been secondary thus far, as the original intent of affordability was 'housing for all'. The inclusion of energy efficiency measures that positively impact operation & maintenance (O&M) costs and thermal comfort requires knowledge, skill, and a unique understanding of the market perspective. As a result, industry stalwarts from leading relevant organisations were identified, and one-on-one virtual meetings/discussions were held in 2021, due to the COVID-19 pandemic. The discussions focused on the following:

1. Validating recommendations from the literature review

2. Grouping passive strategies for each type of climate (identified in previous sections) based on their impacts on cooling load, comfort, and associated costs, as detailed below:

Group 1	Group 2	Group 3
Highly Recommended Strategies	Medium Recommended Strategies	Less Recommended Strategies

3. Ranking low-energy cooling strategies for each identified climate based on their impacts on cooling load, comfort, and associated costs, as detailed below:

Rank 1	Rank 2
Highly Recommended Strategies	Medium Recommended Strategies

The inclusion of energy efficiency measures that positively impact operation & maintenance (O&M) costs and thermal comfort requires knowledge, skill, and a unique understanding of the market perspective. As a result, industry stalwarts from leading relevant organisations were identified, and one-on-one virtual meetings/discussions were held in 2021, due to the COVID-19 pandemic.

4. Assigning weightage to passive vs. low-energy cooling strategies

5. Assigning weightage to cooling load, comfort, and cost

6. Additional remarks and feedback

7. When considering the costs involved, priority grouping was made on the following basis:

   - Group 1: lowest costs involved
   - Group 2: medium costs involved
   - Group 3: high costs involved

All these studies were done for the following four cooling-dominated climates:

- Hot & dry
- Warm-humid
- Composite
- Temperate.

Groups 1, 2, and 3 cover nine strategies, however the individual strategies are not ranked from 1 to 9. Since building physics is a broad spectrum, and multiple variables are involved in decision-making, the standardisation of strategies inherently involves several assumptions and neglects certain variables that need to be studied on a case-by-case basis. While Groups 2 & 3 should not be neglected, 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. Quantifying these strategies in terms of reduction in cooling load and cost factors is beyond this report's scope. There are very few studies that focus on the common and widely accepted strategies that can be standardised. Furthermore, since any standardised recommendations will vary based on the site-specific context, arriving at a list of ranked recommended strategies is challenging. Hence, this report is based on expert stakeholders' responses across the country.

Since building physics is a broad spectrum, and multiple variables are involved in decision-making, the standardisation of strategies inherently involves several assumptions and neglects certain variables that need to be studied on a case-by-case basis.

4.1 Analysis and findings

The responses were collated and analysed, and conclusions were drawn from them on three topics:

1. Passive cooling strategies
2. Low-energy cooling strategies
3. Recommendations on the building envelope.

4.1.1 Passive cooling strategies

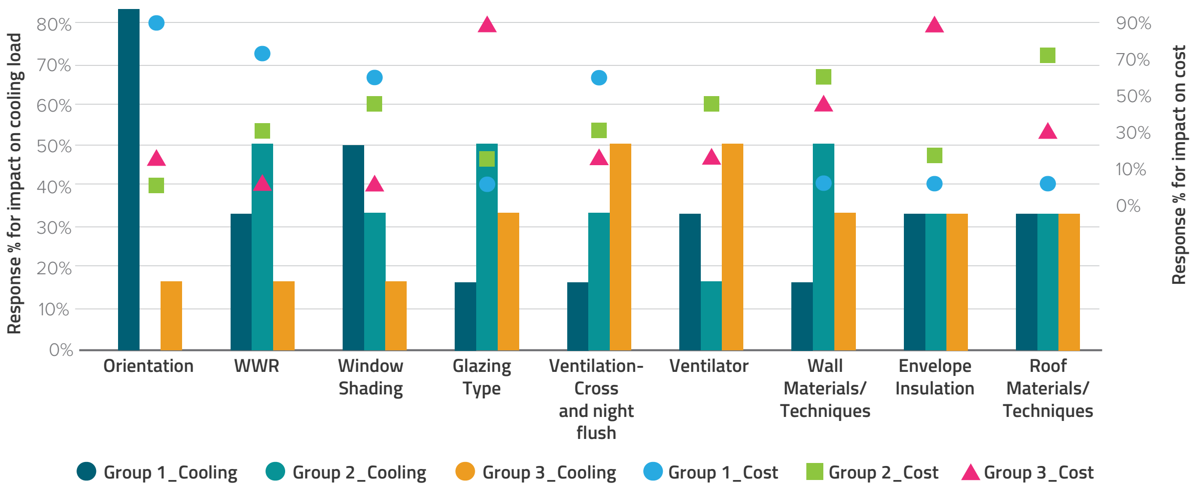
The passive strategies considered were covered in the one-on-one consultations, and results were obtained for each climate when the cooling load and cost were optimised. This section analyses the results based on various climates, as shown in Figure 10 to Figure 13. The bars indicate the response percentage for impact on cooling load, as labelled in the primary y-axis, and the circles indicate the response percentage for impact on cost, as labelled in the secondary y-axis. The tables following each graph summarises findings for grouping of strategies for the respective climates

For hot & dry climates, stakeholder consultation findings indicate that orientation, WWR, and window shading are the highest-impact strategies considering cooling load reduction potential, cost implication and feasibility of implementation in affordable housing.

Hot & dry

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 10. 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 (as shown in primary y-axis) and 86% selected it to be a Group-1 strategy based on cost implications (as shown in secondary y-axis) as well

Figure 10 : Hot & dry - response % for impact on cooling load vs. cost for priority groups



For warm-humid climates, **findings from stakeholder consultation indicate that orientation, cross and night flush ventilation and design of ventilators are the highest-impact strategies. considering cooling load reduction potential, cost implication and feasibility of implementation in affordable housing.**

Table 19 : Hot & Dry climate findings summary after post processing based on weightages assigned

Group 1	Orientation	WWR	Window shading
Group 2	Ventilators	Ventilation- cross and night flush	Roof materials/ techniques
Group 3	Wall Materials/ Tech-niques	Glazing type	Envelope insulation

Warm-humid

For warm-humid climates, findings from stakeholder consultation indicate that orientation, cross and night flush ventilation and design of ventilators 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 WWR, window shading 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 11. It can be observed from the graph that for warm-humid climate, 67% of the experts selected orientation to be a Group-1 strategy based on cooling load (as shown in primary y-axis) and 86% selected it to be a Group-1 strategy based on cost implications (as shown in secondary y-axis) as well.

Figure 11 : Warm-humid - response % for impact on cooling load vs. cost for priority groups

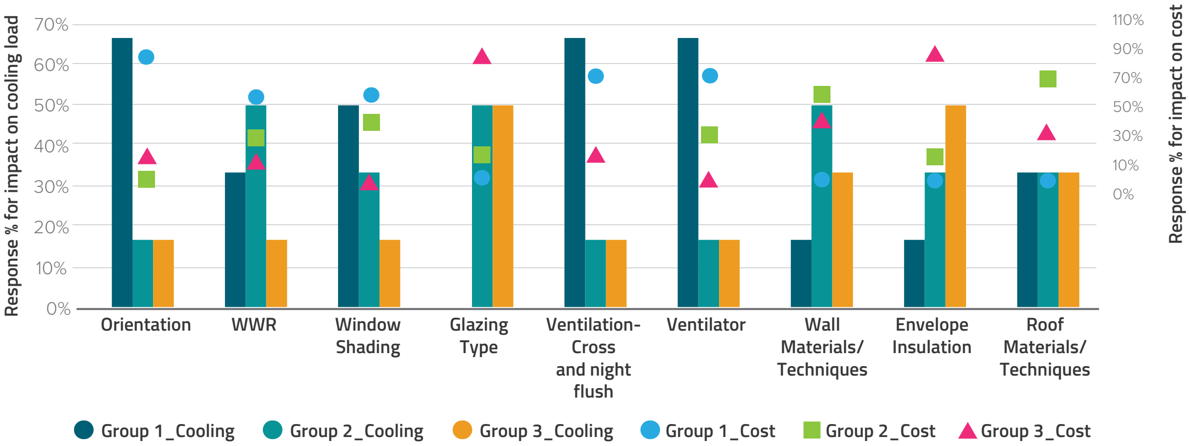


Table 20 : Warm-humid climate findings summary after post processing based on weightages assigned

Group 1	Orientation	Ventilation- cross and night flush	Ventilators
Group 2	WWR	Window shading	Roof materials/ techniques
Group 3	Wall Materials/ Tech-niques	Glazing type	Envelope insulation

Composite

For composite climatic conditions, findings from stakeholder consultation 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 12. The results are similar to hot & dry climatic conditions.

For composite climatic conditions, findings from stakeholder consultation indicate that orientation, WWR, and window shading are the highest-impact strategies. considering cooling load reduction potential, cost implication and feasibility of implementation in affordable housing.

Figure 12 : Composite - response % for impact on cooling load vs. cost for priority groups

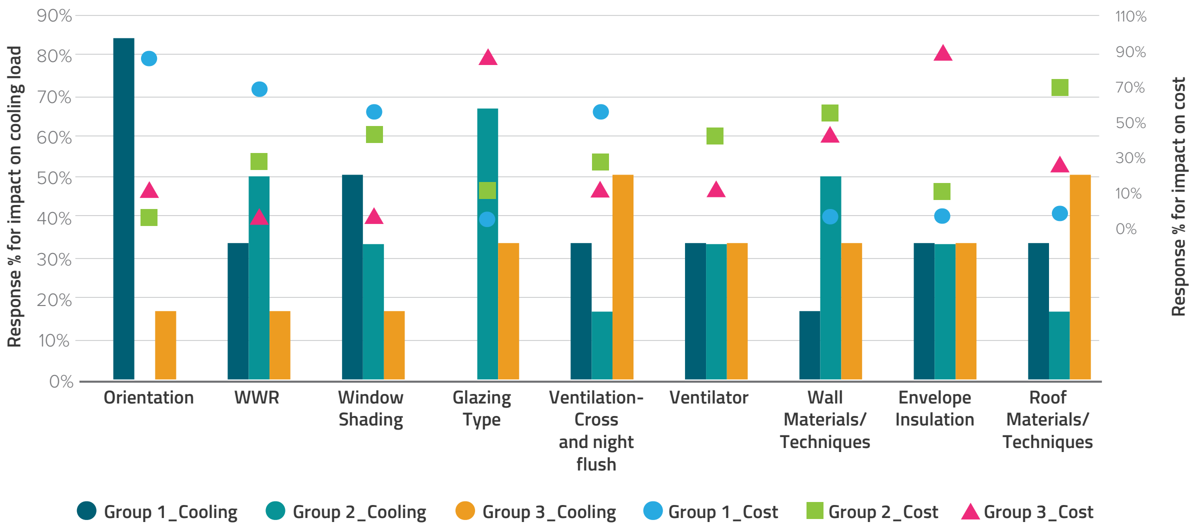


Table 21 : Composite climate findings summary after post processing based on weightages assigned

Group 1	Orientation	WWR	Window shading
Group 2	Ventilators	Ventilation- cross and night flush	Roof materials/ techniques
Group 3	Wall Materials/ Tech-niques	Glazing type	Envelope insulation

Temperate

For temperate climates, stakeholder consultation findings indicate that orientation, window shading, and cross & night flush ventilation are the highest-impact strategies. considering cooling load reduction potential, cost implication and feasibility of implementation in affordable housing.

For temperate climates, stakeholder consultation findings indicate that orientation, window shading, and cross & night flush ventilation 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) are WWR, design of ventilators, and roof assembly strategies. The lowest-impact strategies (Group-3) are glazing assembly, envelope insulation, and wall assembly strategies. The results are depicted in the graph in Figure 13. It can be observed from the graph that for temperate climate, 67% of the experts selected orientation to be a Group-1 strategy based on cooling load (as shown in primary y-axis) and 86% selected it to be a Group-1 strategy based on cost implications (as shown in secondary y-axis) as well.

Super-efficient fans are the most recommended low energy cooling strategy across all climates, considering both energy efficiency and thermal comfort.

Figure 13 : Temperate - response % for impact on cooling load vs. cost for priority groups

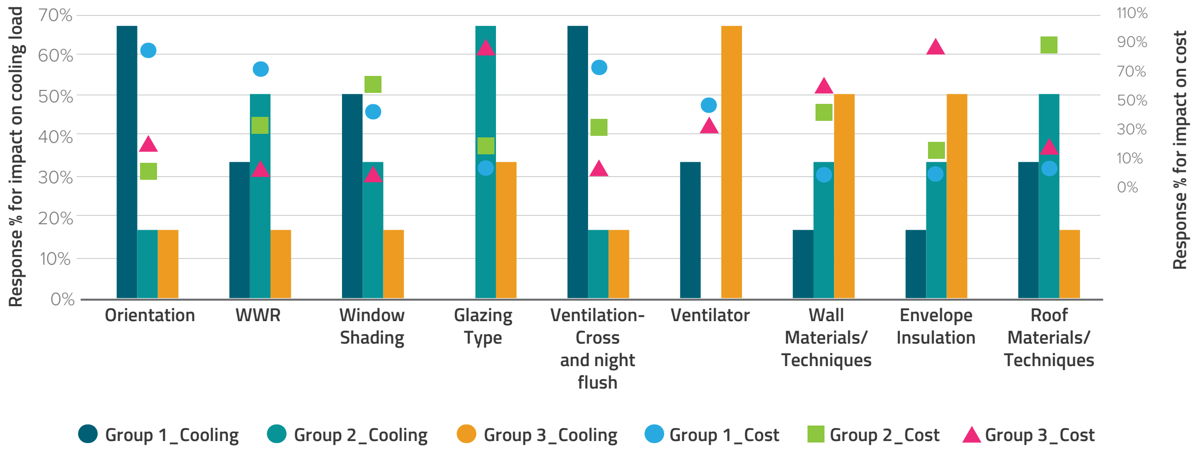


Table 22 : Temperate climate findings summary after post processing based on weightages assigned

Group 1	Orientation	Window shading	Ventilation- cross and night flush
Group 2	WWR	Ventilators	Roof materials/ techniques
Group 3	Wall Materials/ Techniques	Glazing type	Envelope insulation

As per the findings, nine strategies were categorised into three groups of three strategies each for each type of climate. From the cooling load reduction potential 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 optimised with cost findings. Weightages for Groups 1, 2, and 3 were assigned as 50%, 30%, and 20% and normalised to a group weightage of 200 using a multi-criteria approach (Annexure II, Sheet 7).

Experts do not strongly recommend radiant cooling systems, due to their high initial cost and the need to install an additional ventilation system.

4.1.2 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 19 that super-efficient fans are the most recommended Rank 1 strategy across all climates, considering both energy efficiency and thermal comfort. They are followed by evaporative cooling systems, which are mainly recommended due to their cost-effectiveness and value for money. DECs are recommended for all climates except warm-humid climates.

In a warm-humid climate, 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 compared to super-efficient fans and evaporative cooling.

Table 23 : Final climate-wise ranking of low-energy cooling strategies

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

4.1.3 Recommendations - passive and low-energy cooling technologies

The overall findings from the previous sections have been divided into various priority groups, as shown in Table 24, wherein for passive strategies, orientation is in Group 1 for all climates and roof materials/ techniques are in Group 2 for all climates. Group 3 strategies (wall materials & techniques, glazing type, and envelope insulation) are constant across all climates, primarily due to the cost implications involved and resulting lack of affordability. For low-energy cooling strategies, the ranking has been done for all climates, and the results are also valid in terms of installation time and scalability. Experts do not strongly recommend radiant cooling systems as already mentioned in the previous section, due to their high initial cost and the need to install an additional ventilation system. This makes it unsuitable for affordable housing. However, with the necessary funding, it could be possible.

Table 24 : Final recommendations passive and low-energy cooling strategies

PASSIVE COOLING STRATEGIES				
Climate	HOT & DRY	WARM-HUMID	COMPOSITE	TEMPERATE
Group 1	Orientation	Orientation	Orientation	Orientation
	WWR	Ventilation- Cross and night flush	WWR	Window Shading
	Window shading	Ventilators	Window shading	Ventilation - cross and night flush
Group 2	Ventilators	WWR	Ventilators	WWR
	Ventilation- cross and night flush	Window Shading	Ventilation - cross and night flush	Ventilators
	Roof materials/ techniques	Roof materials/ techniques	Roof materials/ techniques	Roof materials/ techniques
Group 3	Wall materials/ techniques	Wall materials/ techniques	Wall materials/ techniques	Wall materials/ techniques
	Glazing type	Glazing type	Glazing type	Glazing type
	Envelope insulation	Envelope insulation	Envelope insulation	Envelope insulation
LOW-ENERGY COOLING STRATEGIES				
Rank 1	Super-efficient fans	Super-efficient fans	Super-efficient fans	Super-efficient fans
Rank 2	Direct evaporative cooling	Indirect evaporative cooling	Direct evaporative cooling	Direct evaporative cooling

4.1.4 Recommendations - building envelope materials

The priority grouping of passive strategies and ranking of low-energy 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 summarised in Table 25 in non-ranked order.

Table 25 : Envelope material recommendations

		Hot & dry	Warm-humid	Composite	Temperate
Wall Materials		AAC	AAC	AAC	AAC
		Clay bricks	Clay bricks	Cellular concrete	Clay bricks
		Hollow bricks	Hollow bricks	Hollow bricks	Hollow bricks
		Fly ash	Cellular concrete	Fly ash	Fly ash
Roof Materials	ROOF - all climates				
	Roof material	Lime concrete, mud-phuska			
	Roof 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	Envelope insulation - all climatic conditions				
	Insulation material	EPS, fiberglass, mineral wool			
	Additional recommen-dations	■ Insulation decisions depend on cost ■ Insulation for roof more preferred than walls ■ Simple insulation will suffice for basic thermal comfort			

For walls, experts recommend 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. Although there was some mild variation in responses across experts, the majority considers India to be predominantly hot while taking design decisions and during the selection of envelope materials.

BEE has recently launched a "Handbook of Replicable Designs for Energy Efficient Residential Buildings," which provides basic design templates to be used by developers and also end-users to design and develop homes that are thermally comfortable and energy-efficient. The Handbook on Replicable Design[90] has been referred to for the design templates for urban and rural affordable housing. The designs relevant to affordable housing are presented in Annexure-III of this report.

90 Bureau of Energy Efficiency (BEE), Handbook of Replicable Designs for Energy Efficient Residential Buildings.

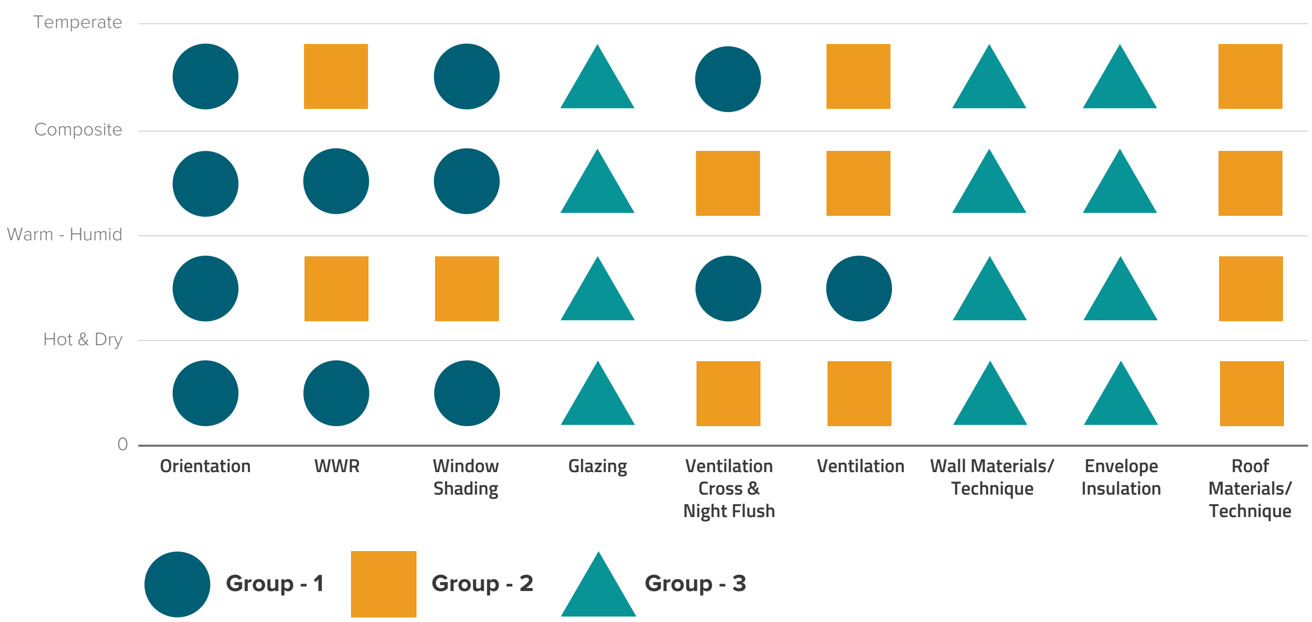
05 CONCLUSION

Comfort cooling is essential to ensure a reasonable standard of living for all. Although there are different income groups, people's perceived thermal comfort does not vary much. The small range of variation in thermal comfort from person to person is mainly due to the human body's ability to adapt to changing climatic conditions. This explains why the urban poor can feel comfortable at higher temperatures than the rest of the urban population—their threshold for heat tolerance is higher. Nonetheless, they still need basic comfort cooling, due to increasing urban heat islands and heat waves taking higher and higher tolls every year.

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 schemes and incentives focused on incorporating energy efficiency into affordable housing. The aim of this study is to help facilitate provision of basic thermal comfort to all through sustainable design measures and green construction. In this regard, passive cooling strategies are more suitable for affordable housing, considering energy efficiency and cost implications. Recommendations provided in this study holds good for affordable housing across India. However, these are not exclusive and prescriptive if the project has scope for detailed climate and energy analysis. Various energy efficiency levels can be achieved, through approaches ranging from implementing basic designs, to adopting best practices, to running complex energy simulations and analysis. This study aims to enable relevant stakeholders like investors, developers, and architects to take the first step towards sustainability, considering fundamentally enhanced cooling and low cost. Figure 14, Table 22, and Table 21can assist investors and developers in decision-making on incorporating energy efficiency into affordable housing by selecting appropriate passive strategies, low-energy cooling strategies, and building materials, respectively. As mentioned above, starting with Group 1 does not mean it is recommended to neglect Groups 2 and 3; rather, it simply means that stakeholders should take the first step with Group 1.

This study aims to enable relevant stakeholders like investors, developers, and architects to take the first step towards sustainability, considering fundamentally enhanced cooling and low cost.

Figure 14 : Climate-wise passive strategy priority grouping



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.

2 Across India, only Bangalore is considered as having a temperate climate. Hence, experts' perception of India from a thermal perspective is 'hot', with a mix of hot & dry, warm-humid, and composite climates. This resulted in nearly identical sets of building materials being recommended by each expert for all climates.

3 Group 3 strategies are the same across all climates, including temperate: glazing, wall materials & techniques, and envelope insulation. The main reason for these strategies' low ranking in relation to affordable housing is their high cost.

Orientation and window shading are the most recommended passive strategies across all climates except warm-humid where ventilation is recommended among group 1.

Table 26 : Final climate-wise ranking of low-energy cooling strategies

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

4. For low-energy cooling strategies, recommendations are constant across all climatic conditions, although specific types within the systems vary (as in the case of evaporative cooling systems), as shown in Table 22. Super-efficient fans like BLDC fans rank the first, and evaporative cooling systems rank second. Super-efficient fans are unanimously ranked as first mainly because of their affordability and short payback period. These tangible benefits can lead to mass retrofitting of conventional fans to super-efficient fans in EWS and

Experts recommend AAC and hollow bricks for walls, lime concrete and mud-phuska for roofs, and EPS, fiberglass, and mineral wool for insulation.

LIG housing sectors through a national scheme. This will also be in alignment with ICAP recommendations.

5. Concerning building materials and construction, a list of materials has been derived from the expert stakeholder consultations, as already shown in Table 21. 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 similar (in most cases).

6. There are incentives and subsidy schemes to promote affordable housing. However, there are no incentives for incorporating energy efficiency within the affordable housing sector.

7. The one-on-one expert stakeholder consultations led to numerous learnings in terms of technical responses and behavioural patterns connected to the responses provided. These learnings can be incorporated into upcoming research and development.

In a scenario where air conditioning is vital, RACs' usage patterns and sizing will change due to the incorporation of passive or low-energy cooling strategies, eventually reducing the use of HCFC refrigerants.

The recommended building materials do not use HCFCs in any form and can be implemented in affordable housing. Recommended passive and low-energy cooling strategies reduce loads on the building and enable more comfortable living conditions than in a BAU scenario. As the limited purchasing power of affordable housing inhabitants inherently poses a challenge for them to purchase an RAC, it is essential to provide thermally comfortable living conditions. In a scenario where air conditioning is vital, RACs' usage patterns and sizing will change due to the incorporation of passive or low-energy cooling strategies, eventually reducing the use of HCFC refrigerants.

Furthermore, the selection of RACs with non-HCFC refrigerants is recommended and can be promoted to the inhabitants through the developers. This would be more feasible if developers formed partnerships with vendors to meet these requirements. These recommendations are specific to affordable housing as a whole, as they are optimised results in terms of cooling load, cost, feasibility, and experts' market perception. HCFC phase-out in the buildings sector for affordable housing can be achieved if these fundamental strategies are followed. At the same time, these recommendations are also relevant for any residence that aims for affordable best practices and thermally comfortable living conditions.

5.1 Further scope of study

In the context of a growing population, increasing affordability, and the changing climate, MoEF&CC elevated the future of cooling in India to a national priority through the ICAP. The ICAP recommends extending government support towards targeted programmes to enable thermal comfort for the EWS and LIG groups as a priority. This approach aims to address a fundamental question rooted in social equity issues, along with technical and environmental ones: with extreme heat, areas of high relative humidity, and a significant portion of the population with limited access to air conditioning (~8% in Indian homes), how does one provide thermal comfort to all affordably and sustainably?

Super-efficient fans like BLDC fans rank the first, and evaporative cooling systems rank second.

ASHRAE defines thermal comfort as 'that condition of mind that expresses satisfaction with the thermal environment.' Thermal comfort in this context cannot be evaluated or quantified using classical thermal comfort indicators (e.g. Fanger's thermal comfort indices Predicted Mean Vote (PMV) or Predicted Percentage of Dissatisfied (PPD)) that are meant for controlled thermal environments. As most affordable housing projects are naturally ventilated, 'thermal comfort' in this study indicates 'adaptive thermal comfort.' The Indian Model for Adaptive Comfort (IMAC) is an adaptive thermal comfort model based on thermal comfort as perceived by Indians. It indicates that Indians' thermal comfort ranges are wider for naturally ventilated and mixed-mode building users.

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 prioritised, along with energy efficiency. Addressing thermal comfort and energy efficiency in affordable housing, this study has provided recommendations based on traditional design principles and assesses factors like cooling load and affordability. To understand and contextualise 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:

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 prioritised, along with energy efficiency.

Quantification of passive strategies' cooling load reduction and cost

As mentioned in the approach and methodology section, this study is qualitative. To arrive at ideal solutions, it is recommended that building energy simulations and cost analyses specific to the relevant market be undertaken. Quantitative results in percentage ranges and specific case studies with building energy simulations can provide an appropriate range that building professionals can rely on for decision-making.

Pilot implementation and hand holding for developers to incorporate energy efficiency into affordable housing

As put forth in the study, recruiting an energy consultant for an affordable housing project may not be entirely feasible, considering the lack of funds in most cases. This necessitates pilot implementation and hand holding for developers and investors to incorporate energy efficiency and analyse the costs incurred as learnings for future affordable housing projects.

Decoding developers' incentives for incorporating energy efficiency into affordable housing

The PMAY-U currently has various schemes for affordable housing loan subsidies and builders' construction concessions. However, there is no mention of the adoption of energy efficiency or incentives for the same. Thus, developers' incentives need to be decoded.

Economic, social, and environmental changes post-adoption of energy efficiency in affordable housing

Successful incorporation of energy efficiency into affordable housing can lead to significant energy savings in India, enhance people's quality of life, and have a positive impact on economic, social, and environmental aspects. Research on these impacts is necessary to develop additional proposals on affordable housing and increase its feasibility.

Business incentives and potential for affordable housing material vendors and minimum quality benchmarks

Successful pilot implementation of energy efficiency measures in affordable housing can help fuel growth in green business for local vendors and suppliers. This, in turn, can lead to green market transformation and increased product quality, benchmark setting, and material labelling.

Eco-labelling of materials

An indirect increase in the purchase of green products in the previous case can also lead to more demand for eco-labelled materials. A rise in the affordable housing implementation rates could significantly enhance the purchasing power of certain income groups, leading to an overall boost to the economy. A proportional increase in the demand for material eco-labelling could therefore necessitate the development of further eco-labelling in the near future.

Integrated approach towards energy-efficient buildings at the Master Plan level

Certain parameters such as orientation that were found to be the most impactful and least-cost measures cannot always be adopted due to the planning of internal roads in the master plan. If the land parcel is large, it is still feasible to manage and modify the orientation. However, in the case of plotted colonies, it is impossible to change the orientation once the plotting is done as per the master plan. Therefore, when developing the master plan, the orientation of buildings' front facades should be kept in mind, and the roads should be planned accordingly.


B-1

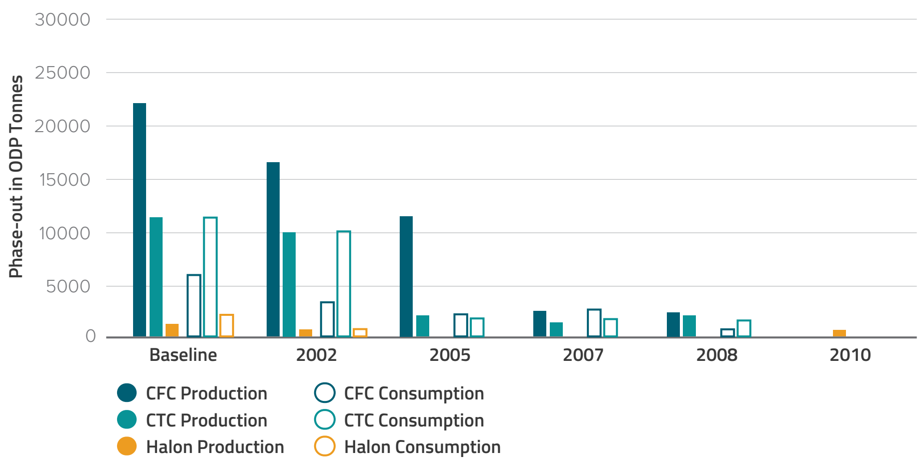
ANNEXURE 1

1.1 International initiatives to tackle ozone depletion and monitor HCFC use

Montreal Protocol

The 'Montreal protocol on substances that deplete the ozone layer' is the trademark multilateral environmental agreement designed to protect the ozone layer by phasing out the production and consumption of nearly a hundred man-made chemicals categorised as 'Ozone Depleting Substances.' The protocol entered into force in 1989. It is the only treaty that has been ratified by all 198 member-states of the United Nations and is legally binding. The protocol includes provisions related to several issues under different 'Articles.' Article 5 deals with the 'Special situation of developing countries.' It phases down the ODS stepwise with varying timetables for developed and developing countries (known as 'Article 5' countries'). It was amended in 1990, 1992, 1995, 1997, 1999, and 2016. India has also successfully followed these timelines and phased out CFCs and halons. In 2007, the parties decided to accelerate the HCFC phase-out. Developed countries had targeted phasing out 100% HCFCs from the baseline by 2020. In contrast, developing countries were scheduled to initiate their phase-out process in 2013 through the HPMP and complete it by 2030. China is the largest producer and consumer of HCFCs. India only produces HCFC-22; all other HCFCs that are in use are imported. India initiated activities in early 2009. Figure 15 shows the phase-out of high ODS production and consumption over the past two decades, along with the baseline [91 92 93].

Figure 15 : **High ODS production and consumption phase-out**



91 Ozone Cell, MoEF&CC, Government of India, and UNDP, "HPMP Stage-1 for Compliance with the 2013 and 2015 Control Targets for Consumption of Annex-C, Group-1 Substances," 2015.

92 Ozone Cell, MoEF&CC, UNEP, and EESL, "HCFC Phase-Out and Energy Efficiency in Buildings," 2017.

93 Ozone Cell, MoEF&CC, Government of India, "HCFC PHASE-OUT MANAGEMENT PLAN Stage-II," 2017.

Kigali Amendment

HFCs are currently used as alternatives to HCFCs and CFCs, as they are not ozone-depleting substances; however, they are greenhouse gases (GHGs) that are potent and long-lasting and magnify the global warming effect. Hence, they have a high GWP. As a result, 197 countries arrived at a historic agreement on phasing out HFCs under the ambit of the Montreal protocol at the 28th Meeting of Parties held in Kigali Rwanda, in 2016. This amendment, known as the 'Kigali amendment to the Montreal Protocol,' aimed for countries to achieve an 80-85% reduction in HFC consumption from their respective baselines by 2047. Out of the 122 countries that ratified the Kigali amendment to the Montreal protocol, 90 countries have ratified, 26 countries have accepted, and six countries have approved the Kigali amendment in their respective countries[94]. China ratified it most recently, in June 2021. The expected impact of the amendment is to prevent an increase of a 0.5°C in global temperatures by the end of the century.

197 countries arrived at a historic agreement on phasing out HFCs under the ambit of the Montreal protocol at the 28th Meeting of Parties held in Kigali Rwanda, in 2016. This amendment, known as the 'Kigali amendment to the Montreal Protocol,' aimed for countries to achieve an 80-85% reduction in HFC consumption from their respective baselines by 2047.

The HCFC phase-out limits and the timeline for India as per the Montreal Protocol's maximum allowable consumption of ODS Group 1 substances are shown in Table 23. The consumption limit in 2009-2010 was 1608.2 tonnes of ODP, frozen as the baseline in 2013. The proposed phase-out intends to reduce ODP consumption to zero by 2040.

Table 27 : HCFC phase-out limits for India[95]

Montreal Protocol Maximum Allowable Consumption of Level of Annex C Group 1 Substance	Consumption Limit (ODP Tons)
Baseline (2009-2010 average)	1608.20
2013 - Freeze on baseline levels	1608.20
2015 - 90% of the baseline	1447.38
2020 - 65% of the baseline	1045.33
2025 - 32.5% of the baseline	522.67
2025 - 2.5% of the baseline	40.21
2040 - No Consumption	0

1.2 Alternatives: low-GWP refrigerant materials

In order to meet the targets under the Montreal Protocol, HCFCs need to be phased out. At present, HFCs are the group of alternative refrigerants to the CFCs and HCFCs, as they have zero ozone depletion potential. Nevertheless, they have a significant GWP when released into the atmosphere and need to be phased down over time. Therefore, there needs to be an increase in the use of non-HFCs, HFOs, natural refrigerants, and low-GWP alternatives as refrigerants.[96]

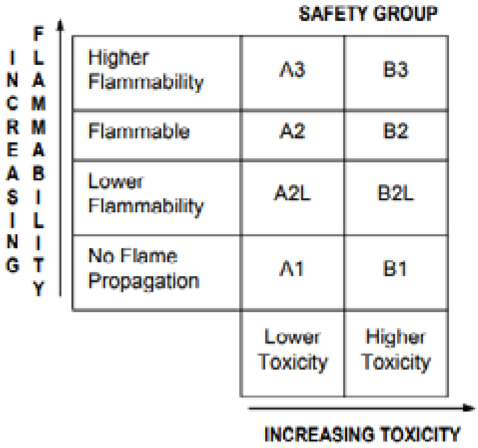
94 United Nations, "Amendment to the Montreal Protocol on Substances That Deplete the Ozone Layer," n.d.

95 Ozone Cell, MoEF&CC, Government of India, "HCFC PHASE-OUT MANAGEMENT PLAN Stage-II."

96 Ministry of Environment, Forest & Climate Change, Government of India, "HCFC Phase-Out And Energy Efficiency In Buildings" (New Delhi, 2017), http://ozone-cell.in/wp-content/themes/twentyseventeen-child/Documentation/assets/pdf/1511262726987-HCFC-Booklet-final.pdf.

An ideal refrigerant should have low GWP, a medium pressure range, and evaporating pressure above atmospheric pressure to avoid air intake into the system. It should also be safe, i.e. non-toxic & non-flammable, have zero ODP, and be environmentally friendly[97 98]. ASHRAE's safety group classification of refrigerants is used to define the flammability and toxicity of a refrigerant, as shown below in Figure 16.

Figure 16 ASHRAE's 2018 refrigerant safety group classification[99]



B3 is considered to be highly flammable and toxic, whereas A1 is considered to be the least toxic and flammable refrigerant.

The choice of an alternative refrigerant for RACs depends on several factors, such as the availability of the refrigerant, convenience in applicability and cost of the refrigerant and the associated equipment, energy efficiency of the system, associated safety, environmental issues, etc[100]. Such refrigerants are listed in Table 28.

Table 28 : Refrigerants used in air conditioners

Sub-sector	Commonly used alternatives/ substitutes	ODP	GWP
Room AC	R-410A	0	2088
	HC-290	0	3
	HFC-32	0	675
Packaged AC	R-410A	0	2088
	R407C	0	1774
	HFC-32	0	675
	HC-290	0	3

97 O B Tsvetkov et al., "Alternative Refrigerants with Low Global Warming Potential for Refrigeration and Air-Conditioning Industries," in IOP Conference Series: Materials Science and Engineering, vol. 905 (IOP Conference Series: Materials Science and Engineering, 2020), https://doi.org/10.1088/1757-899X/905/1/012070.

98 W Goetzler et al., "Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants," 2014.

99 ASHRAE, "Designation and Safety Classification of Refrigerants," 2018.including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE website (www.ashrae.org

100 Ibid.

ANNEXURE 2

Questionnaire discussed during expert stakeholder consultations

Sheet-1: Receiving inputs on passive strategies

Sheet-2: Priority grouping of strategies based on cooling load

Sheet-3: Priority grouping of strategies based on cost

Sheet-4: Priority grouping of strategies based on thermal comfort

Sheet-5: Ranking of low-energy cooling strategies

Sheet-6: Feedback

Sheet-7: Multi-criteria design assessment tool

Sheet-1: Receiving inputs on passive strategies

Passive and Low Energy Cooling Srategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing						
From Literature reviews, existing few case studies/ research on affordable housing in India and from Eco Niwas Samhita, the following table has been created. Please give your inputs. NOTE that ranking of these strategies based on different criteria like cooling demand reduction potential, impact on thermal comfort and cost is addressed in the following sheets. THIS SHEET ONLY INTENDS TO LAY OUT ALL THE BEST OPTIONS						
Sl.no	**PASSIVE STRATEGIES**	**General Recommendation under passive strategy**	**Agree/ Disagree (with reason)**	**Remarks if 'Disagree'**	**Final responses (Auto generated)**	**Remarks**
1	Orientation	N-S predominantly	Agree		N-S predominantly	
		NW-SE - option-2	Agree		NW-SE - option-2	
2	WWR	<30%	Agree		<30%	
3	Window Shading	South- horizontal	Agree		South- horizontal	
		East & West- Vertical	Agree		East & West- Vertical	
		North- Optional	Agree		North- Optional	
4	Glazing type (select)	Single glazing - E,W, N	Agree		Single glazing - E,W, N	
		Double glazing- South only	Agree		Double glazing- South only	
5	Ventilation- cross and night flush	Openings on 2 sides of room with WWR<30% each with min.WFR	Agree		Openings on 2 sides of room with WWR<30% each with min.WFR	
6	Ventilators	2' high ventilators above 7' in habitable areas	Agree		2' high ventilators above 7' in habitable areas	
7	Wall materials/ tech-niques	Please select/ mention most preferred 4 materials (from below or any others) recommended for walls of AH considering COST & PERFORMANCE		Select/ mention any 4 for each climate	Final responses (Auto generated)	Remarks
		Below are commonly available materials in India as per ENS				
		Solid burnt clay brick		Hot & Dry:	Hot & Dry:	
		Hollow brick			0	
		Flyash brick		Warm-Humid:	Warm-Humid:	
		Solid concrete block			0	
		AAC block		Composite:	Composite:	
		CSEB			0	
		RCC		Temperate:	Temperate:	
		Lime concrete			0	
		Cellular concrete			0	

8	Envelope insulation	Please select/ mention most recommended insulation material for building envelope- roof and walls of AH considering COST & PERFORMANCE Below are commonly available materials in India without HCFCs	Select/ mention any 3 for each climate	Final responses (Auto generated)	Remarks
		Note that some insulation materials like PU, Extruded Polystyrene, Phenolic foam, Polyethylene use HCFC during their manufacturing as blowing agents.			
		Fibreglass	Hot & Dry (walls):	Hot & Dry (walls):	
			Hot & Dry (Roofs):	Hot & Dry (Roofs):	
		Mineral wool	Warm-Humid (walls):	Warm-Humid (walls):	
			Warm-Humid (Roofs):	Warm-Humid (Roofs):	
		Cellulose	Composite (walls):	Composite (walls):	
			Composite (Roofs):	Composite (Roofs):	
		Glass wool	Temperate (walls):	Temperate (walls):	
			Temperate (Roofs):	Temperate (Roofs):	
9	Roof materials/ techniques	Please select most preferred 4 materials/ technologies (from below or any others) recommended for roofs of AH considering COST & PERFORMANCE Below are commonly available materials in India as per ENS	Select/ mention any 2 materials for roofs and 2 other techniques (construction techniques/ surface treatment like tiles and SRI paint etc)	Please select most preferred 4 materials/ technologies (from below or any others) recommended for roofs of AH considering COST & PERFORMANCE	Remarks
		Brick tile	Hot & Dry (materials):	Hot & Dry (materials):	
			Hot & Dry (techniques):	Hot & Dry (techniques):	
		Lime concrete	Warm-Humid (materials):	Warm-Humid (materials):	
			Warm-Humid (techniques):	Warm-Humid (techniques):	
		Mud phuska	Composite (materials):	Composite (materials):	
			Composite (techniques):	Composite (techniques):	
		AC sheet	Temperate (materials):	Temperate (materials):	
			Temperate (techniques):	Temperate (techniques):	
Note: For envelope, we will be calculating the RETV values in compliance with Eco Niwas Samhita after arriving at the top 5 materials (as post-survey analysis) based on literature review and expert consultation. Hence we are not getting inputs on U-value, SGHC, VLT etc as preference is given more to affordability, scalability and feasibility for affordable housing					

Sheet-2: Priority grouping of strategies based on cooling load

Passive and Low Energy Cooling Srategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing

If the best recommendation for each of the listed strategies were adopted, how would you **rank these strategies** for different climatic conditions for REDUCING COOLING LOAD. *Base case here is assumed to be Naturally ventilated residential building*

	RANKING BASED ON COOLING LOAD REDUCTION POTENTIAL- Group 1-3						
	STRATEGIES	**CRITERIA**	**CLIMATIC ZONES**				
	If you have to rank these strategies as Group-1,2,3 (Group1- high impact; Group-2 Medium impact; Group-3 Low impact) on **reducing cooling loads i**n affordable housing in India?	Final recommendations (responses from previous sheet will be carried over)	Hot & Dry (3 strategies in each group)	Warm-Humid (3 strategies in each group)	Composite (3 strategies in each group)	Temperate (3 strategies in each group)	Remarks
1	Orientation	N-S predominantly					
		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	Openings on 2 sides of room with WWR<30% each with min.WFR					
6	Ventilators	2' high ventilators above 7' in habitable areas					
7	Wall materials/ techniques	Hot & Dry:		NA	NA	NA	
		0		NA	NA	NA	
		Warm-Humid:	NA		NA	NA	
		0	NA		NA	NA	
		Composite:	NA	NA		NA	
		0	NA	NA		NA	
		Temperate:	NA	NA	NA		
		0	NA	NA	NA		
		0	NA	NA	NA		
8	Envelope insulation	Hot & Dry (walls):		NA	NA	NA	
		Hot & Dry (Roofs):		NA	NA	NA	
		Warm-Humid (walls):	NA		NA	NA	
		Warm-Humid (Roofs):	NA		NA	NA	
		Composite (walls):	NA	NA		NA	
		Composite (Roofs):	NA	NA		NA	
		Temperate (walls):	NA	NA	NA		
		Temperate (Roofs):	NA	NA	NA		
9	Roof materials/ techniques	Hot & Dry (materials):		NA	NA	NA	
		Hot & Dry (techniques):		NA	NA	NA	
		Warm-Humid (materials):	NA		NA	NA	
		Warm-Humid (techniques):	NA		NA	NA	
		Composite (materials):	NA	NA		NA	
		Composite (techniques):	NA	NA		NA	
		Temperate (materials):	NA	NA	NA		
		Temperate (techniques):	NA	NA	NA		
Would you say that the same ranking would be valid for Thermal Comfort as well?							

LEGENDS	
Group-1	High impacting measures
Group-2	Medium impacting measures
Group-3	Low impacting measures

Sheet-3: Priority grouping of strategies based on cost

Passive and Low Energy Cooling Srategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing							
Based on the previous sheet, **if the best recommendation for each of the listed strategies were adopted**, how would you **rank these strategies** for different climatic conditions for REDUCING COST. *Base case here is assumed to be Naturally ventilated residential building*							
RANKING BASED ON COOLING LOAD REDUCTION POTENTIAL- Group 1-3							
	STRATEGIES	**CRITERIA**	**CLIMATIC ZONES**				
	If you have to rank these strategies as Group-1,2,3 (Group1-high impact; Group-2 Medium impact; Group-3 Low impact) on **reducing cost i**n affordable housing in India?	Final recommendations (responses from previous sheet will be carried over)	Hot & Dry (3 strategies in each group)	Warm- Humid (3 strategies in each group)	Composite (3 strategies in each group)	Temperate (3 strategies in each group)	Remarks
1	Orientation	N-S predominantly					
		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	Openings on 2 sides of room with WWR<30% each with min.WFR					
6	Ventilators	2' high ventilators above 7' in habitable areas					
7	Wall materials/ techniques	Hot & Dry:		NA	NA	NA	
		0		NA	NA	NA	
		Warm-Humid:	NA		NA	NA	
		0	NA		NA	NA	
		Composite:	NA	NA		NA	
		0	NA	NA		NA	
		Temperate:	NA	NA	NA		
		0	NA	NA	NA		
		0	NA	NA	NA		
8	Envelope insulation	Hot & Dry (walls):		NA	NA	NA	
		Hot & Dry (Roofs):		NA	NA	NA	
		Warm-Humid (walls):	NA		NA	NA	
		Warm-Humid (Roofs):	NA		NA	NA	
		Composite (walls):	NA	NA		NA	
		Composite (Roofs):	NA	NA		NA	
		Temperate (walls):	NA	NA	NA		
		Temperate (Roofs):	NA	NA	NA		

9	Roof materials/ techniques	Hot & Dry (materials):		NA	NA NA	NA	
		Hot & Dry (techniques):		NA	NA	NA	
		Warm-Humid (materials):	NA		NA	NA	
		Warm-Humid (techniques):	NA		NA	NA	
		Composite (materials):	NA	NA		NA	
		Composite (techniques):	NA	NA		NA	
		Temperate (materials):	NA	NA	NA		
		Temperate (techniques):	NA	NA	NA		

LEGENDS	
Group-1	High impacting measures
Group-2	Medium impacting measures
Group-3	Low impacting measures

Sheet-4: Priority grouping of strategies based on thermal comfort

Passive and Low Energy Cooling Srategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing							
Based on the previous sheet, **if the best recommendation for each of the listed strategies were adopted**, how would you **rank these strategies** for different climatic conditions for ENHANCING THERMAL COMFORT. *Base case here is assumed to be Naturally ventilated residential building*							
RANKING BASED ON THERMAL COMFORT ENHANCEMENT POTENTIAL- Group 1-3							
	STRATEGIES	**CRITERIA**	**CLIMATIC ZONES**				
	If you have to rank these strategies as Group-1,2,3 (Group1- high impact; Group-2 Medium impact; Group-3 Low impact) on **enhancing thermal comfort i**n affordable housing in India?	Final recommendations (responses from previous sheet will be carried over)	Hot & Dry (3 strate-gies in each group)	Warm- Hu-mid (3 strate-gies in each group)	Composite (3 strate-gies in each group)	Temperate (3 strate-gies in each group)	Remarks
1	Orientation	N-S predominantly					
		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	Openings on 2 sides of room with WWR<30% each with min. WFR					
6	Ventilators	2' high ventilators above 7' in habitable areas					
7	Wall materials/ techniques	Hot & Dry:		NA	NA	NA	
		0		NA	NA	NA	
		Warm-Humid:	NA		NA	NA	
		0	NA		NA	NA	
		Composite:	NA	NA		NA	
		0	NA	NA		NA	
		Temperate:	NA	NA	NA		
		0	NA	NA	NA		
		0	NA	NA	NA		

8	Envelope insulation	Hot & Dry (walls):		NA	NA	NA	
		Hot & Dry (Roofs):		NA	NA	NA	
		Warm-Humid (walls):	NA		NA	NA	
		Warm-Humid (Roofs):	NA		NA	NA	
		Composite (walls):	NA	NA		NA	
		Composite (Roofs):	NA	NA		NA	
		Temperate (walls):	NA	NA	NA		
		Temperate (Roofs):	NA	NA	NA		
9	Roof materials/ techniques	Hot & Dry (materials):		NA	NA	NA	
		Hot & Dry (techniques):		NA	NA	NA	
		Warm-Humid (materials):	NA		NA	NA	
		Warm-Humid (techniques):	NA		NA	NA	
		Composite (materials):	NA	NA		NA	
		Composite (techniques):	NA	NA		NA	
		Temperate (materials):	NA	NA	NA		
		Temperate (techniques):	NA	NA	NA		

LEGENDS	
Group-1	High impacting measures
Group-2	Medium impacting measures
Group-3	Low impacting measures

Sheet-5: Ranking of low-energy cooling strategies

Passive and Low Energy Cooling Srategies for Achieving Thermal Comfort in India's Upcoming Affordable Housing

For low energy cooling technologies, we have laid out a selected few strategies here. The feasibility of aDopting to low energy systems when compared to passive strategies is lower. Hence this sheet intends to capture ONE RANKING ORDER (to address cooling demand, thermal comfort and cost altogether) and rank the strategies into Rank-1, 2 and 3.

Sl.no	LOW ENERGY COOLING STRATEGIES	Types/ categories	Hot & Dry (Mention Rank-1, 2 or 3)	Warm- Humid (Mention Rank-1, 2 or 3)	Temperate (Mention Rank-1, 2 or 3)	Composite (Mention Rank-1, 2 or 3)	Time/ease of installation/ implementation ease (Mention Rank-1, 2 or 3)	Scalability (Mention Rank-1, 2 or 3)	Remarks	
1	Evaporative cooling	Direct Evap cooling								
		Indirect evap cooling								
		I-D Evap cooling								
2	BLDC fans (Brush Less DC)	NA								
3	Radiant cooling	Through Ceiling								
		Through Floor								
		Through Walls								
4	Desiccant cooling	NA								
5	Any other low energy cooling strategy	NA								
6	Any other low energy cooling strategy	NA								

WEIGHTAGE OF CRITERIA FOR AFFORDABLE HOUSING						
We have surveyed primarily for 3 main parameters. What weightage would you provide for these (out of 10)			Weightage	COLOR CODED LEGENDS		
	Cooling load reduc-tion		*Rank-1*			
	Thermal comfort		*Rank-2*			
	Cost		*Rank-3*			
	TOTAL OF 10	**0**				
	Weightage					
	Passive					
	Low Energy					
	TOTAL OF 10	**0**				

Sheet-6: Feedback

Energy Efficiency and Thermal Comfort in India's Upcoming Affordable Housing Creating Resilient, Efficient, Sustainable Thermal comfort Solutions for Affordable Housing CREST solutions for Affordable Housing	
FOLLOW-UP / FEEDBACK QUESTIONS	
For affordable housing, what challenges do you find in this project and how do you think we can address them?	
What kind of improvisation would you like to propose to this project?	
Any other questions and suggestions welcome.	
THANK YOU FOR THE TIME	

Sheet-7: Multi-criteria design assessment tool

Strategy Evaluation Tool

Step #1: Weighting
Give each criteria its own weight.
Assign each interest category a weight by allocating 100 points among the *n* categories.
Weights can take on any value between zero to 100.
The more important the interest, the higher its weight.
The sum of the scores for all weights should add up to 100, otherwise go to step 2

Step #2: Normalization
Normalize the assigned weights to each category.

Since, it maybe difficult to assign weights that they add up to 100, normalization is required.

Step #3: Scoring
How well does each alternative satisfy the criterion ?"
Use a 'best to worst' ranking or a numeric scale:
5=excellent;
4=very good;
3=fair;
2=below average;
1=poor.

Step #4: Total Score
Calculate the score for each strategy option by multiplying the individual score of each strategy by its criteria weight.
Sum the scores within each strategy to derive the total strategy score.

Description					Scoring								
S.No.	Criteria	Group Weight	Criteria Weight	Normalized Weight	Orientation	WWR	Window Shading	Glazing type	Ventilation- Cross and night flush	Ventilators	Wall materials/ techniques	Envelope insulation	Roof materials/ techniques
1	Group 1		50	25.00	5	2	3	1	1	2	1	2	2
2	Group 2		30	15.00	0	3	2	3	2	1	3	2	2
3	Group 3		20	10.00	1	1	1	2	3	3	2	2	2
4	**Cost**			0.00									
5	Group 1	200	50	25.00	6	5	4	0	4	3	0	0	0
6	Group 2		30	15.00	0	2	3	1	2	3	4	1	5
7	Group 3		20	10.00	1	0	0	6	1	1	3	6	2

		Total Score								
S.No.	Criteria	Orientation	WWR	Window Shading	Glazing type	Ventilation- Cross and night flush	Ventilators	Wall materials/ techniques	Envelope insulation	Roof materials/ techniques
1	Group 1	125.00	50.00	75.00	25.00	25.00	50.00	25.00	50.00	50.00
2	Group 2	0.00	45.00	30.00	45.00	30.00	15.00	45.00	30.00	30.00
3	Group 3	10.00	10.00	10.00	20.00	30.00	30.00	20.00	20.00	20.00
4	**Cost**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Group 1	150.00	125.00	100.00	0.00	100.00	75.00	0.00	0.00	0.00
6	Group 2	0.00	30.00	45.00	15.00	30.00	45.00	60.00	15.00	75.00
7	Group 3	10.00	0.00	0.00	60.00	10.00	10.00	30.00	60.00	20.00
Total Score		**295.00**	**260.00**	**260.00**	**165.00**	**225.00**	**225.00**	**180.00**	**175.00**	**195.00**
Ranking		**1**	**2**	**2**	**9**	**4**	**4**	**7**	**8**	**6**

Orientation	295
WWR	260
Window Shading	260
Ventilation- Cross and night	225
Ventilators	225
Roof materials/ techniques	195
Wall materials/ techniques	180
Envelope insulation	175
Glazing type	165

ANNEXURE 3 – BUILDING DESIGN TEMPLATES[101]

Affordable housing sizes are based on income categories. It should be noted that the allowable size of units is up to 30 m^2 for EWS, 60 m^2 for LIGs, 160 m^2 for MIG-I, and 200 m^2 for MIG-II. BEE recently launched a "Handbook of Replicable Designs for Energy Efficient Residential Buildings", which encapsulates basic design templates that could be used by both developers and end-users to design and develop homes that are thermally comfortable and energy-efficient. It comprises design templates based on areas ranging from 30 m^2 to 300 m^2, which are categorised as per Table 29.

Table 29 : Eligibility slab of affordable housing based on income, unit size, and loan interest subsidy[102]

Economic sections as per PMAY-U	Annual household income range (INR)	Unit size (m^2)
EWS	Up to 3 lakh	Up to 30
LIG	3-6 lakh	Up to 60
MIG-I	6-12 lakh	Up to 160
MIG-II	12-18 lakh	Up to 200

The set of plans has been designed for predominantly tropical climate regions, including hot & dry, warm-humid, composite, and temperate climate zones. The primary design strategy is to reduce solar heat gain and heat gain from ambient air and optimise ventilation to remove internal heat, which should directly lead to improvement in thermal comfort. The templates recommended are made based on a north-south orientation.

3.1 For urban areas: low-rise (ground + 3) row houses: 2 BHK

The floor plan catalogue has designs ranging from small one-bedroom, hall, & kitchen (BHK) units to large 4 BHK units. The 2 BHK category, which is common in LIG housing and the most prevalent type of housing across India in urban areas, is presented below in Figure 17.

101 Bureau of Energy Efficiency (BEE).

102 Ministry of Housing & Urban Poverty Alleviation, Government of India, Pradhan Mantri Awas Yojana - Housing for All (Urban) - Scheme Guidelines 2015.

Figure 17 : Low-rising housing site, block, and floor plan

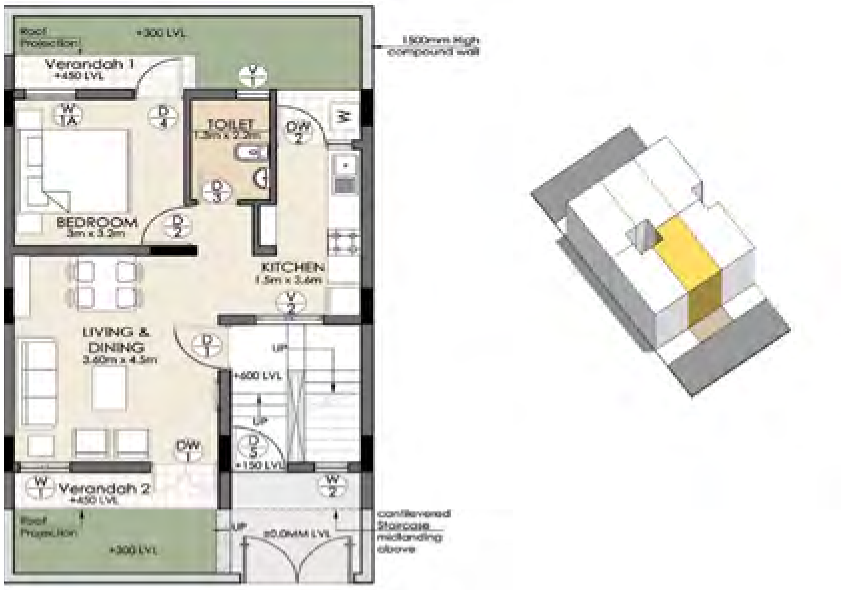
3.2 For Rural Areas: Plotted Single Family Houses

Plotted developments are defined by the size of plots and the number of sides the building is open to the outside. There can be three types of floor layouts, as defined in the BEE's Handbook of Replicable Design: single side open, two side open, and three side open or semi-detached. These three types are described below:

1. Single side open plot

In dense urban areas, many single-owner plots are now converting to low-rise buildings, with each family occupying a floor. When designing for single-family homes, this provision for future expansion needs to be accommodated. This single side plot can be elevated to up to 2-3 floors, depending on the state building byelaws regarding the plot size and permitted floor area ratio (FAR). The plot size of the floor plan shown in Figure 18 is 80 m^2, and the carpet area is 38 m^2 .

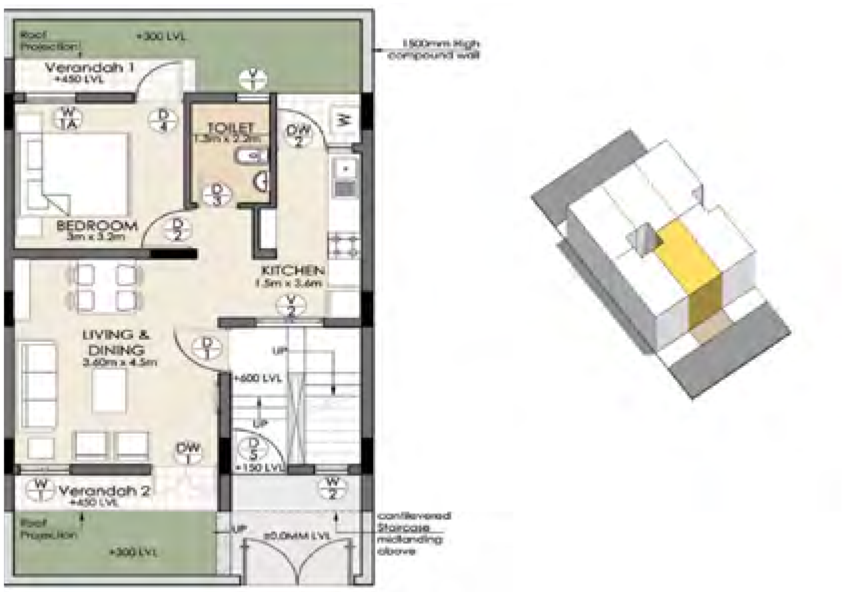
Figure 18 : Design template for single side open plot



2. Two side open plot

In warm-humid or temperate climate zones, the ventilation requirements may not be met by a single side open plot. Therefore, the two side open row house typology is adopted in such cases. This opens to the front street, as well as a back street or a back setback, while the side walls remain shared with the neighbours. These plots can also be elevated to up to 3-4 floors, depending on the state building byelaws regarding the plot size and permitted FAR. The plot size of the floor plan shown in Figure 19 is 160 m^2, and the carpet area is 77 m^2

Figure 19 : Design template for two side open plot



3. Semi-detached or three side open plot

The setback guidelines as defined in the National Building Code (NBC) suggest that for larger plot sizes, setbacks are required on three sides. This leads to the semi-detached typology, which has one shared wall and is open on three sides. When dealing with larger plots, internal courtyards or shafts can be introduced to meet the light & ventilation needs. The plot size of the floor plan shown in Figure 20 is 200 m², and the carpet area is 90 m².

Figure 20 : Design template for semi-detached or three side open plot

3.3 Construction components and specifications

The construction components and specifications presented below are suggested as per the north-south orientation of the buildings. The specifications can be adopted for each climate type, i.e. hot & dry, warm-humid, composite, and temperate zones, and most affordable housing projects. The energy performance indices (EPIs) mentioned are specific to 2 BHK low-rise housing units (ground + 3). However, most of the low-rise buildings in urban areas and plotted colonies in rural areas developed as per the specifications given below. The recommended solutions mentioned in the report should be in a similar EPI range. Construction components and specifications per climate zone are summarised below in Table 30:

Table 30 : Component and material specifications

Components and specifications			
BASE	MODERATE	GOOD	HIGH
EPI: 54.36 kW/Mt²	**EPI:** 50.36 kW/Mt²	**EPI:** 43.06 kW/Mt²	**EPI:** 35.04 kW/Mt²
Wall – 230 mm Brick	**Wall** – 200 mm AAC block	**Wall** – 200 mm AAC block	**Wall** – 200 mm AAC block with 50 mm thick EPS insulation
Roof – 50 mm EPS insulation + light-coloured glazed tile	**Roof** – 50 mm EPS insulation + light-coloured glazed tile	**Roof** – 50 mm EPS insulation + light-coloured glazed tile	**Roof** – 50 mm EPS insulation + light-coloured glazed tile

Window – Single glazed unit with rolled steel frame	**Window** – Single glazed unit with rolled steel frame	**Window** – Double glazed unit with UPVC frame	**Window** – Double glazed unit with UPVC frame
Shading – No shading	**Shading** – Additional top and side shading fins & roll down bamboo screens for balcony	**Shading** - Additional top and side shading fins & roll down bamboo screens for balcony	**Shading** - Additional top and side shading fins & roll down bamboo screens for balcony
Electro-mechanical systems – 3-star rated appliances	**Electro-mechanical systems** – 3-star rated appliances	**Electro-mechanical systems** – 4-star rated appliances	**Electro-mechanical systems** – 5-star rated appliances

NOTE for reading the table:

1. Base here refers to the base case or least efficient case that is still ECBC compliant.
2. The EPIs have been calculated for buildings with a north-south orientation.
3. Moderate, Good, and High refer to building energy performance and heat load reduction potential in ascending order respectively when compared to the base case.
4. The abovementioned components and specifications shall be reviewed in accordance with the complete Handbook on Replicable Designs by BEE.

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