IETP
India Energy Transformation Platform
Decarbonising India

DEVELOPING COST-EFFECTIVE AND LOW-CARBON OPTIONS TO MEET INDIA'S SPACE COOLING DEMAND IN URBAN RESIDENTIAL BUILDINGS THROUGH 2050

Knowledge partner: *Greentech Knowledge Solutions Pvt. Ltd; energe-se and Centre for Advanced Research in Building Science & Energy, CEPT University*

Secretariat: *Center for study of Science, Technology & Policy*

Supported by: *Shakti Sustainable Energy Foundation and Swiss Agency for Development & Cooperation*

Please cite this report as:

Maithel, S., Chandiwala, S., Bhanware, P., Rawal, R., Kumar, S., Gupta, V., Jain, M. (2020, June). Developing cost-effective and low-carbon options to meet India's space cooling demand in urban residential buildings through 2050. India Energy Transformation Platform.

India Energy Transformation Platform (IETP)

The India Energy Transformation Platform is a multi-stakeholder group of experts in the field of energy, technology and policy. The Platform identifies crucial developments and technology solutions to look at long-term pathways for decarbonising India's energy sector up to 2050. IETP was conceptualised by the Swiss Agency for Development and Cooperation (SDC) and Shakti Sustainable Energy Foundation (SSEF), with Center for Study of Science, Technology and Policy as the secretariat. In its first year, the Platform identified four themes - decentralised energy systems, renewable energy technologies, industrial process heating and urban space cooling - to look at non-linear, transformational technology and policy solutions for decarbonising India.

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1 Introduction and Literature Review

1.1 Context

Space cooling is the fastest growing energy use in buildings globally (IEA, 2018). Multiple studies have looked at space cooling demand projections for India, and a sharp increase is expected in the next two to three decades. By 2050, 45% of India's peak electricity demand is expected to come from space cooling alone (IEA, 2018). A large part of this future demand has been attributed to the adoption of room air conditioners (RAC), and 80%–90% of the RAC stock is expected to be concentrated within the residential sector by 2037/38 (MoEFCC, 2019). India alone could be home to over 1 billion air conditioners, making its energy consumption for cooling one of the highest in the world (IEA, 2018). As a result, the residential sector needs to be at the forefront for initiatives aimed at meeting India's space cooling requirement sustainably by 2050.

Recent studies provide useful insights into space cooling requirement and associated cooling electricity demand from the residential sector in the next two to three decades. In most of the studies, the strategy to reduce electricity use for space cooling is largely focused on the use of highly energy efficient or low-energy space cooling technologies, with inadequate focus on measures for envelope optimization to reduce the cooling load. This does not adequately address the nature of the space cooling energy demand in the residential sector, which is driven primarily by heat ingress related to climatic conditions and building characteristics, as opposed to commercial buildings where significant heat loads are generated internally from people and equipment.

Climate-related characteristics such as temperature, humidity, and the duration of the cooling period determine the need for space cooling. Building envelope-related characteristics determine how much heat ingress occurs and the subsequent need for active space cooling technologies to achieve comfort. Hence, an efficient building envelope can help reduce the space cooling requirement itself. Efficient cooling technologies can further help by meeting this reduced space cooling requirement with lower amounts of energy.

Apart from this, focusing entirely on efficient cooling technology solutions does not factor the impact on thermal comfort,[1] heath, and productivity of people who are unable to afford these technologies. There is currently wide variation in electricity use in households in India. A 2014 analysis (IEA, 2015) shows the state-wise distribution of residential energy consumption per capita in the country, of the population that currently has access to electricity. Delhi, as the urbanized city state, has the highest electricity consumption per capita at 600 kWh, while this figure is only 50 kWh in Bihar, which lacks a reliable and continuous supply of electricity. Access to space cooling will require both access to adequate and reliable electricity, and the ability to afford cooling technologies, if cooling technologies alone are prioritized in space cooling policy initiatives. This implies that only people who can afford these technologies can be assured of thermal comfort. However, constructing efficient buildings will improve comfort and effectively reduce the requirement for space cooling, irrespective of these limitations of access to electricity and cooling technologies.

[1] Human body continuously generates heat and this heat must be rejected to the surroundings to remain thermally comfortable. Thermal comfort is that condition of thermal environment under which a person can maintain a body heat balance at normal body temperature and without perceptible sweating.

Under the business-as-usual (BAU) scenario, a recent report by the International Labor Organization (ILO, 2019) suggests that in India it is expected to lose equivalent of 34 million full-time jobs in 2030 as a result of heat stress. Additionally, incidents of heat waves have increased globally because of the increase in temperatures related to climate change as well as urban heat islands in the cities. This will further exacerbate the requirement for space cooling to achieve thermal comfort, especially for India's climate. Thermal comfort is hence integral to a decent quality of life and needs to be recognized as a development need in India.

There has been no attempt at the policy-making level to visualize the quality of life and a decent standard of housing that would define this development paradigm in India, where thermal comfort is recognized as a necessity and not just restricted to those who can afford currently available space cooling technologies. This is similar to how in cold countries there is a debate on recognizing the 'right to warmth' and prioritizing action to reduce energy poverty (Walker Gordon, 2015). A study on the cooling needs of the Global South (IIASA) (Mastrucci et al., 2019) already brings forth this dimension in the space cooling debate and estimates the cooling gap, in addition to the electricity access gap in countries in the Global South.

Within this context, this study creates a detailed bottom-up framework for assessing the space cooling energy requirement and associated cooling electricity demand from India's urban residential sector from 2020 to 2050. The framework prioritizes thermal comfort requirements for all households, based on the policy vision of 'thermal comfort for all' as mentioned in the India Cooling Action Plan (ICAP) and recommends solutions for achieving deep cuts in this demand.

1.2 Study Objective and Scope

The objective of this study is to assess low-carbon and cost-effective solutions for achieving deep cuts in space cooling requirement and associated cooling electricity demand from India's urban residential sector during 2020–2050.

Scope:

- The scope of the study is limited to urban residential buildings where a majority of the RAC applications are foreseen in the immediate future.
- It is limited to assessment of cooling technologies at the house, building, or personal level. Technology solutions at the urban scale, such as district cooling, have not been considered, as urban models would need to be employed to assess their impact. This is not possible within the scope and time constraints of this study.

1.3 Methodology

The methodology for the study consists of four steps (Figure 1):

i. Critical review of recent cooling demand estimation studies
ii. Detailed bottom-up framework for modelling space-cooling requirement for enabling the policy vision of 'thermal comfort for all'.
iii. Evaluation of building envelope and cooling technologies for reducing space cooling requirement and cooling electricity demand.
iv. Recommendations for policy action.

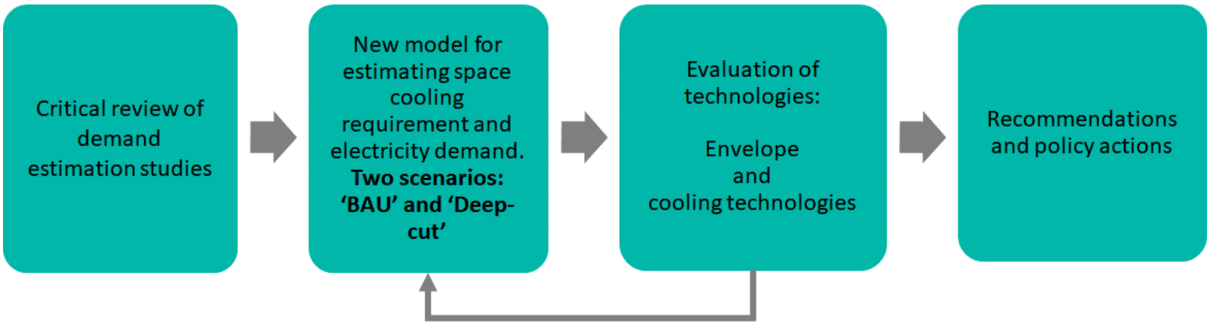
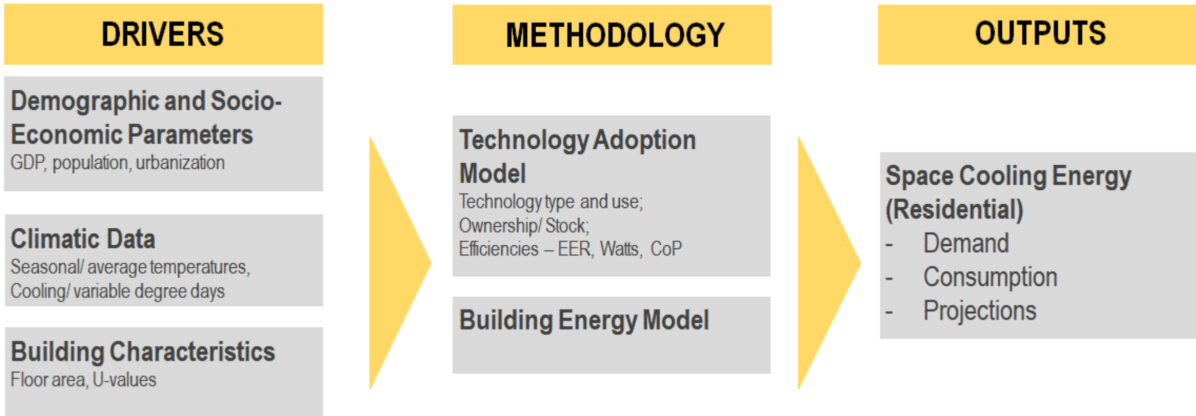


Figure 1: Methodology of the study

1.4 Literature Review

This study looked at recent literature on India's space cooling and residential energy demand assessment and identified six key studies. These studies adopt a combination of three main space cooling demand-side drivers to project residential space cooling energy consumption: demographic and socio-economic, climatic data, and building characteristics (Figure 2).



Note: Framework derived from IIASA (Mastrucci et al., 2019).

Figure 2: Illustration representing the modelling approach of the studies

Based on a detailed assessment of the methodology and results, these six studies were classified into two broad categories:

- **Impact of supply-side measures (space cooling technologies):** These studies use various demand-side drivers to arrive at the likely increase in the use and type of prevalent cooling technologies. Scenarios for reduction in projected space cooling electricity demand are largely based on possible efficiency improvements in cooling technologies.
- **Impact of both demand-side (building envelope characteristics, U-values) and supply-side (space cooling technologies) measures:** These studies also look at building characteristics as a determinant of space cooling electricity demand, in addition to prevalent space cooling technologies. Projected scenarios assess efficiency improvements in both building envelope performance and cooling technologies to arrive at possible reductions in space cooling electricity demand.

These six studies are discussed below in brief to highlight their objectives, approach, results, and observations.

1.4.1 Impact of supply-side measures (space cooling technologies)

Three studies – IEA (2018), MoEFCC (2019), and LBNL (de la Rue du Can et al., 2019) – primarily assess space cooling electricity demand based on existing cooling technologies and how they are used (running hours, set point temperature for cooling, etc.). The methodology includes understanding the current stock and future adoption rates of cooling technologies. Scenarios are based on efficiency improvements in these technologies, with the assumption that no breakthrough technology comes to the market.

India Cooling Action Plan (MoEFCC, 2019)

Objective: The India Cooling Action Plan (ICAP) provides a 20-year outlook (2017/18 to 2037/38) on cooling requirements and its associated energy demand across sectors – space cooling in buildings, cold chain and refrigeration, and transport air conditioning.

ICAP provides an overview of the present cooling electricity demand in buildings and available technologies and projects energy use for future cooling demand under two alternative scenarios – reference (business-as-usual [BAU] policy status) and intervention (positive impacts of new technology, policy, and market drivers). While the study focuses on all types of buildings and cooling technologies, the focus was on results that align with residential buildings and its technologies, and hence only data on RACs, fans, and evaporative air coolers are discussed.

Drivers: The study estimates the current adoption rates and stock of cooling technologies from multiple sources**,** including the Bureau of Energy Efficiency (BEE)'s Standards and Labelling Programme and information gathered from the industry. Information on building floor area and urban and rural households has been accessed from the National Sample Survey Organization (NSSO 2011) and Census 2011. It refers to the IESS model for assumptions on demographic and socio-economic parameters of GDP, population (appliance penetration), urbanization, and income growth to project the future increase in adoption and stock and the resultant cooling energy consumption in 2027 and 2037.

Key results:

- Approximately 8% of the current urban and rural households (2017) in India have RACs, which is expected to rise to 40% by 2037.
- Almost 80%–90% of the total stock of RACs in 2037/38 is likely to be in the residential sector.
- Around 29% reduction in the cooling energy consumption of residential buildings can be achieved in the intervention scenario against the reference scenario.

Table 1: Key results (ICAP study)

Output parameters, ICAP	**Results****		
	2017/18	Reference scenario (2037/38)	Intervention scenario (2037/38)
Annual space cooling electricity consumption in residential buildings (both urban and rural)*	108 TWh	443 TWh	313 TWh

*Analysis includes RACs, fans, and air coolers.
**The annual residential space cooling electricity consumption figures were calculated using mid-point estimates of identified ranges from the annual energy consumption table of Appendix A (Space cooling in buildings) in the ICAP study.

Observations:

- The study recommends 'thermal comfort for all'; but does not provide guidance and methods to achieve it.
- It also highlights the importance of building envelope performance in space cooling demand reduction but does not seem to model this in detail. A modest 10% reduction in annual run time (from 1600 to 1440 hours) for RACs has been factored-in, to account for it.

The Future of Cooling (IEA, 2018)

Objective: The IEA cooling report provides key insights into the current and future trends in cooling across 35 countries and regions, and further assesses the global demand for space cooling in 2050. To reduce this space cooling demand, the report focuses only on one measure – improving the efficiency of RACs – that can generate quick energy savings. It, however, discusses a range of other drivers and policy measures that can also lead to substantial reductions in space cooling demand.

The report assumes that the space cooling requirement of a building is driven by the quantity, efficiency, and usage patterns of RACs and adopts a scenario-based approach to model the air conditioning demand by using its Energy Technology Perspectives (ETP) model. The baseline scenario assumes that everyone who needs an RAC is able to access it, but with BAU policy measures. The other efficient cooling scenario looks at a more rigorous policy outlook and enhanced equipment efficiency such as tighter minimum energy performance standards (MEPS) for RACs. As mentioned above, the study provides a range of global trends in cooling, but based on our focus, only India-specific modelling results are discussed.

Drivers: For residential buildings, it primarily uses the country-specific demographic and socio-economic drivers such as population growth, urbanization, GDP, and per capita income to project the impact of economic growth on the country's cooling demand. It then incorporates technological variables such as the seasonal energy efficiency ratio/energy efficiency ratio to model the energy performance of air conditioning cooling technologies. To account for climate, it uses cooling degree days (CDDs) and incorporates the impact of a 1 °C rise in average global temperature by 2050. On average, CDDs are expected to increase globally by nearly 25% between 2016 and 2050 in the baseline scenario and 20% in the efficient cooling scenario. The setpoint temperature has been assumed to be 18 °C to calculate these. This generates a set of space cooling energy demand by fuel. The report also models cost-effective power capacity mix options to meet this demand during peak and off-peak times. This is based on country-specific assumptions on techno-economic characteristics of power generation technologies such as solar, wind, and coal, along with load profiles for RACs and energy policies.

Key results:

- The wide range in access to space cooling across the world is reflected in the annual per capita levels of energy consumption in 2016. These vary from 70 kWh in India, to more than 800 kWh in Japan and Korea, and 1880 kWh in the United States.
- Share of space cooling in India's peak electricity load will rise from 10% in 2016 to 45% in 2050 in the baseline scenario.
- India's cooling-related electricity demand will reduce by almost 46% in the efficient cooling scenario as compared to the baseline scenario in 2050.

Table 2: Key results (IEA study)

Output parameters, IEA	Results		
	2016	Baseline scenario (2050)	Efficient cooling scenario (2050)
Annual space cooling electricity demand for India buildings sector (both residential and commercial)*	90 TWh	1350 TWh	734 TWh**

*Analysis includes air conditioning, electric fans, and dehumidification in residential and commercial service sectors.
**Calculated from India's share of 22% electricity savings in the total global electricity savings of 2800 TWh/year.

Observations:

- The 2050 baseline scenario in the IEA study is progressive, as it considers that those who require cooling are able to access it and that the required power generation capacity will have to be built.
- The report highlights that in the longer term, larger energy savings are possible through improvement in building envelope performance. It suggests that combined policies for efficient air conditioners and efficient buildings have the potential to keep the demand for cooling flat while allowing growth in access to cooling for populations globally. However, the focus in the report is on the shorter-term measure, accounting only for efficient air conditioners.

Modelling India's Energy Future Using a Bottom-up Approach (LBNL; de la Rue du Can et al., 2019)

Objective: The LBNL report provides an estimate of India's baseline energy consumption and CO_2 emission in 2050 if India follows an economic growth trajectory similar to that followed by China in the last 35 years. The paper provides detailed assumptions on the energy demand drivers for the five sub-sectors (agriculture, industry, transport, residential and commercial buildings, and power). It estimates energy intensity and emissions from each of these sectors. While the study focuses on all the demand sub-sectors, the focus is on results that align with residential buildings, and hence only results related to residential energy consumption have been discussed.

Drivers: For residential buildings, the study models the energy demand of urban and rural households at the end-use level – air conditioning, appliances, cooking and water heating, lighting, and a residual category. It further assigns appropriate technologies and appliances with diffusion rates, energy efficiencies, and fuel types. Demographic and socio-economic parameters used include population and GDP, along with rural and urban household size and area of residential buildings. Air conditioning is identified as one of the critical end-uses contributing to the residential sub-sector demand growth. The NSSO surveys (since 1990) were used for historical data on AC ownership in urban and rural households and also for future projections. BEE data on MEPS is used to assess the efficiency of current stock and sales of RACs.

Key results:

- The annual space cooling electricity consumption in the urban residential sector could rise by almost 6 times in 2050 from the 2015 baseline levels if India follows a growth trajectory similar to that of China in the last 35 years.

Table 3: Key results (LBNL study)

Output parameters, LBNL	**Results****	
	2015	Baseline scenario (2050)
Annual space cooling electricity consumption in urban residential buildings*	125 TWh	736 TWh

*Analysis includes fans and RACs.

**Values are derived visually from graphs, and petajoules values were converted to terawatt-hours (TWh) to calculate the annual space cooling electricity consumption for urban households.

Observations:

- The study describes a detailed bottom-up model that projects India's baseline energy consumption and emissions in 2050 if the macro-economic drivers are at par with the growth trajectory in China in the last 35 years. This defines an alternative and probable growth scenario, instead of following an incremental approach to projecting future growth trajectory.

1.4.2 Impact of both demand-side (building envelope characteristics, U-values) and supply-side (space cooling technologies) measures

Three studies – IESS (2015), GBPN (2014), and IIASA (Mastrucci et al., 2019) – assess space cooling demand based on residential building energy performance characteristics, along with existing cooling technologies and how they are used (running hours, setpoint temperature for cooling, etc.) The methodology uses building energy modelling to understand how the building envelope impacts space cooling demand, followed by the use of cooling technologies to assess cooling energy consumption. Scenarios are based on efficiency improvements in building envelope and cooling technologies, with the assumption that no breakthrough technology comes to the market.

India's Energy Security Scenarios 2047 (NITI Aayog, 2015)

Objective: IESS 2047 is an online energy scenario building tool that provides multiple options for India's future energy demand and supply sectors. This study only refers to the section on efficient envelope optimization for residential and commercial buildings, which aims to reduce building energy consumption through the use of energy-efficient construction materials.

The paper refers to the IESS 2047 model to estimate space cooling demand for the residential sector. It analyses four scenarios – least effort (level 1) to heroic effort (level 4) – to project the space cooling demand. These scenarios assume a progressive compliance to the Energy Conservation Building Code (ECBC) norms, supporting policies for efficient buildings, and higher appliance efficiencies.

Drivers: Residential buildings are classified into rural and urban. Urban houses are further categorized as high-rise development, horizontal (low-rise) development, and affordable housing. The building energy model defines the characteristics of the three building types, including floor area, number of floors, building envelope characteristics, and technology efficiencies and use. To project the four scenarios, demographic and socio-economic parameters of population growth, GDP, and urbanization have been used. The 2012 base case assumes 7.4% CAGR of GDP. Based on this, the residential floor space is assumed to rise from 10.8 m^2 per capita in 2012 to 32.9 m^2 per capita in

2047. Space cooling demand for the four scenarios is estimated by changing the efficiency levels for both building envelope and cooling technologies (ceiling fans and RACs).

Key results:

- Approximately 7% of the urban households in India in 2012 were assumed to have RACs, which is expected to rise to 55% by 2047.
- The residential space cooling and water heating demand can be reduced by about 42% in the 'heroic effort' scenario as compared to the 'least effort' scenario in 2047.

Table 4: Key results (IESS study)

Output parameters, IESS	**Results**		
	Baseline (2012)	Least effort scenario (2047)	Heroic effort scenario (2047)
Annual space heating and cooling electricity demand in residential buildings*	51 TWh	971 TWh	568 TWh

*Analysis includes RACs and fans, along with heating energy use in residential buildings.

Observations:

- The residential floor space will increase from 10.8 m^2 per capita in 2012 to 32.9 m^2 per capita in 2047. The projected per capita residential floor space for 2047 is much higher than that observed in emerging economies like Mexico and developed Asian economies like Korea for comparable levels of per capita GDP (IEA, 2019).
- None of the four scenarios accounts for adoption of building energy codes in affordable housing. This assumes that this segment's space cooling demand requirements will not be met because of affordability issues with respect to efficient building envelope and cooling technologies.
- Assumptions used for modelling are not clearly defined or referenced, which makes it difficult to interpret results. This is a significant gap, as other studies such as ICAP refer to IESS data for assessment.

Residential Buildings in India: Energy Use Projections and Savings Potentials (GBPN, 2014)

Objective: The study assesses residential electricity consumption in India up to 2050 and highlights the long-term energy savings potential. The study also has a specific focus on understanding the role of efficient building envelope in determining the space cooling energy, especially from the use of RACs, in the overall energy savings potential from the sector.

A survey of 800 households was conducted in four cities representing four different climates to understand their electricity consumption patterns and appliance penetrations. This was used to validate the building energy model. The study projects total residential electricity consumption as a measure of three distinct energy use components – energy use due to all appliances (including lighting), the interdependent energy requirement due to building envelope characteristics, and air conditioners across urban and rural households. To assess the energy savings potential, four projection scenarios have been developed – BAU, moderate, aggressive, and very aggressive – by progressively increasing both the adoption rate and efficiency of building envelope (BAU, ECBC,[2] and ECBC+) and only the efficiency of appliances (while the adoption rate remains constant).

[2] Energy Conservation Building Code for Commercial Buildings has been used as a parameter to model building envelope. ECBC+ represents further stringent requirements than the ECBC 2007 version.

Drivers: Projection scenarios are derived using three influencing variables – changes in adoption rate, future increases in efficiency, and increase in usage. It is anticipated that the adoption rate and increase in usage of appliances and air conditioners will increase rapidly in India based on socio-economic parameters of population, access to electricity, and income. These have been kept constant for all scenarios, and only the average efficiency of appliances and air conditioners has been increased.

For building envelope, energy performance depends on adoption of building energy policies. Hence, both adoption rate and the efficiency of building envelope are progressively increased across the four scenarios. Cooling and heating degree days have been used to determine the performance and use of both air conditioners and building envelopes in different climate zones.

Key results:

- In hot and dry, warm and humid, and composite climates, ECBC and ECBC+ envelopes can reduce air conditioning energy consumption by 40% and 66%, respectively. In moderate climates, the impact of ECBC and ECBC+ envelopes can eliminate the need for air conditioning and provide 30% overall savings.
- The very aggressive scenario yields a 59% reduction in the space cooling electricity consumption in urban residential buildings compared to the BAU scenario in 2050.

Table 5: Key results (GBPN study)

Output parameters, GBPN	**Results**		
	2012	BAU scenario (2050)	Very aggressive scenario (2050)
Annual space cooling electricity consumption in urban residential buildings*	13 TWh	345 TWh	141 TWh

*Analysis includes urban AC- and urban envelope-related energy demand

Observations:

- The study represents one of the earlier studies looking at the residential sector energy demand for 2050 and segregates the space cooling demand as a function of building envelope and RACs.
- The baseline results of 13 TWh of annual space cooling electricity demand for 2012 seem much lower than that seen in other studies. This is possibly because AC adoption rates have rapidly increased in the last few years. Projected data from the report shows this to increase to 68 TWh in 2020.

Improving the SDG Energy Poverty Targets: Residential Cooling Needs in the Global South, IIASA (Mastrucci et al., 2019)

Objective: The paper assesses the residential cooling demand for six regions that form the Global South – sub-Saharan Africa, Centrally Planned Asia and China, Latin America and the Caribbean, the Middle East, North Africa, and other Pacific Asia and South Asia. Backed by its hypothesis, to ensure thermal comfort for all, the paper calculates the present cooling demand gap and highlights the size and location of population currently exposed to heat stress. This study has uniquely looked at a more comprehensive measure of energy access, by introducing the dimension of space cooling, which has been largely overlooked so far but has a higher implication for human health and functioning. The study provides an overview of the global cooling needs, but the focus is limited to India-specific results.

Drivers: The paper comprehensively draws upon all the drivers of cooling demand such as demography, socio-economic well-being, climate, and building types to account for technology adoption and building energy modelling. The authors estimate the space cooling needs and population currently affected by the cooling energy poverty gap.

The study defines building envelope parameters for one typical rural and one urban house and evaluates the cooling energy gap from the usage of two appliances, namely AC and fan. The cooling energy needs (kWh/capita/year) are then calculated based on the annual variable degree days[3] on a per capita basis, assuming an indoor setpoint of 26 °C and a floor surface of 10 m^2 per capita. This is later aggregated to the country and global levels. A sensitivity analysis is also conducted to understand the impact of varying indoor temperature setpoints, user behaviour, and building design conditions.

The cooling energy gap[4] is then calculated as the difference between the cooling demand with universal access to fans and AC and the current access to AC and fan. Country-specific AC penetration values were estimated as per the AC penetration model (McNeil et al., 2008; Isaac and van Vuuren, 2009). For fans, the penetration numbers are kept equal to the percentage of electricity access.

Key results:

- The study calculates a 6% penetration of ACs in India and compares it with a 5% penetration estimated by the India Human Development Survey (IHDS) 2010/11.
- 1.1 billion Indians are potentially exposed to heat stress and affected by the cooling gap of 335 TWh/year for an indoor temperature of 26 °C.
- India represents 44% of the total global space cooling gap. This is the highest among all countries that were evaluated.

Table 6: Key results (IIASA study)

Output parameters, IIASA	Results	
	Baseline	Projections
Annual space cooling energy gap in the residential sector*	335 TWh	—

*Analysis includes RACs and fans.

Observations:

- The report estimates the explicit residential cooling needs in the Global South under current climate and socio-economic conditions.
- It highlights the importance of considering residential space cooling requirement alongside other basic energy needs.

1.5 Novel features of our study

The current study makes the following additional contributions to the space cooling demand estimation studies reviewed in Section 1.4:

[3] A variable degree day (VDD) method advances the degree day method by analytically calculating the balance temperature as the outdoor temperature at which neither heating, nor cooling is required (instead of taking a fixed value as in case of a degree day method).

[4] The cooling energy gap is the additional energy needed by everyone to reach to a particular thermal comfort level.

- It extends the scope to enabling 'thermal comfort for all' as a policy vision, by assessing the space cooling requirement and associated cooling electricity demand for all households, and not limiting it by incremental access to cooling technologies. The study also emphasizes thermal comfort as a development need in India, recognizing its impact on health and productivity.
- It creates a detailed bottom-up modelling framework based on granular district-wise data on both building construction characteristics and climate classification. This granularity of data has not been previously used for space cooling demand estimation.
- The study assesses scenarios for improvement in both building envelope and cooling technologies from 2020 to 2050 to enable deep cuts in space cooling demand through low-carbon and cost-effective solutions.
- It provides detailed recommendations related to building envelopes based on the following:
    - Evaluation of the reduction in discomfort degree hours in houses. It focuses on reducing discomfort hours as a solution that greatly benefits households with limited or no access to cooling technologies in maintaining comfortable indoor conditions.
    - Modelling the potential impact of retrofitting existing buildings on space cooling energy reduction, which has not been done so far in India.

2 Estimating Space Cooling Requirement and Cooling Electricity Demand

2.1 Methodology

Space cooling requirement and cooling electricity demand are estimated using a bottom-up approach. Calculations are done for urban households at the district level for each district, which then are summed up to estimate the cooling requirement and electricity demand at the state, climatic zone, and country levels.

The other key consideration for the calculations was the principle of equity, i.e., providing thermal comfort for all the households throughout the year. The demand for cooling energy is estimated for maintaining thermal comfort inside all the houses.

The cooling electricity demand (kWh) will depend upon two factors:

i. Space cooling requirement (in kWh_{th}): The amount of thermal energy that needs to be removed from inside buildings to maintain thermal comfort.

ii. Equivalent coefficient of performance ($CoP_{equivalent}$): It is the ratio of cooling provided (or heat removed) by the cooling system to the energy input to the cooling system. It gives the efficiency at which thermal energy will be removed, i.e., efficiency of the cooling technology employed.

$$\text{Cooling electricity demand (kWh)} = \text{Space cooling requirement } (\text{kWh}_{th})/\text{CoP}_{equivalent}$$

The first factor will depend on the climate and building envelope properties. For a given climate, better thermal performance of the building envelope results in lower heat gains inside the building, i.e., lower amount of thermal energy that needs to be removed to maintain thermal comfort. Hence, this factor will govern the required cooling capacity of the cooling system. The second factor is the characteristic of the cooling technology employed. This will decide the connected load of the cooling system, e.g., for a 1 TR (3.5 kW) cooling capacity air conditioner, with a CoP of 3.1, the connected load would be ~1130 W.

The overall methodology (Figure 3) for estimating the cooling requirement and cooling electricity demand is briefly described here, while the detailed methodology is explained in Annexure A. For this analysis, 2020 is taken as the base year, and all the key parameters are estimated for the years 2020 and 2050 as well as for the intermediate years 2025, 2030, and 2040.

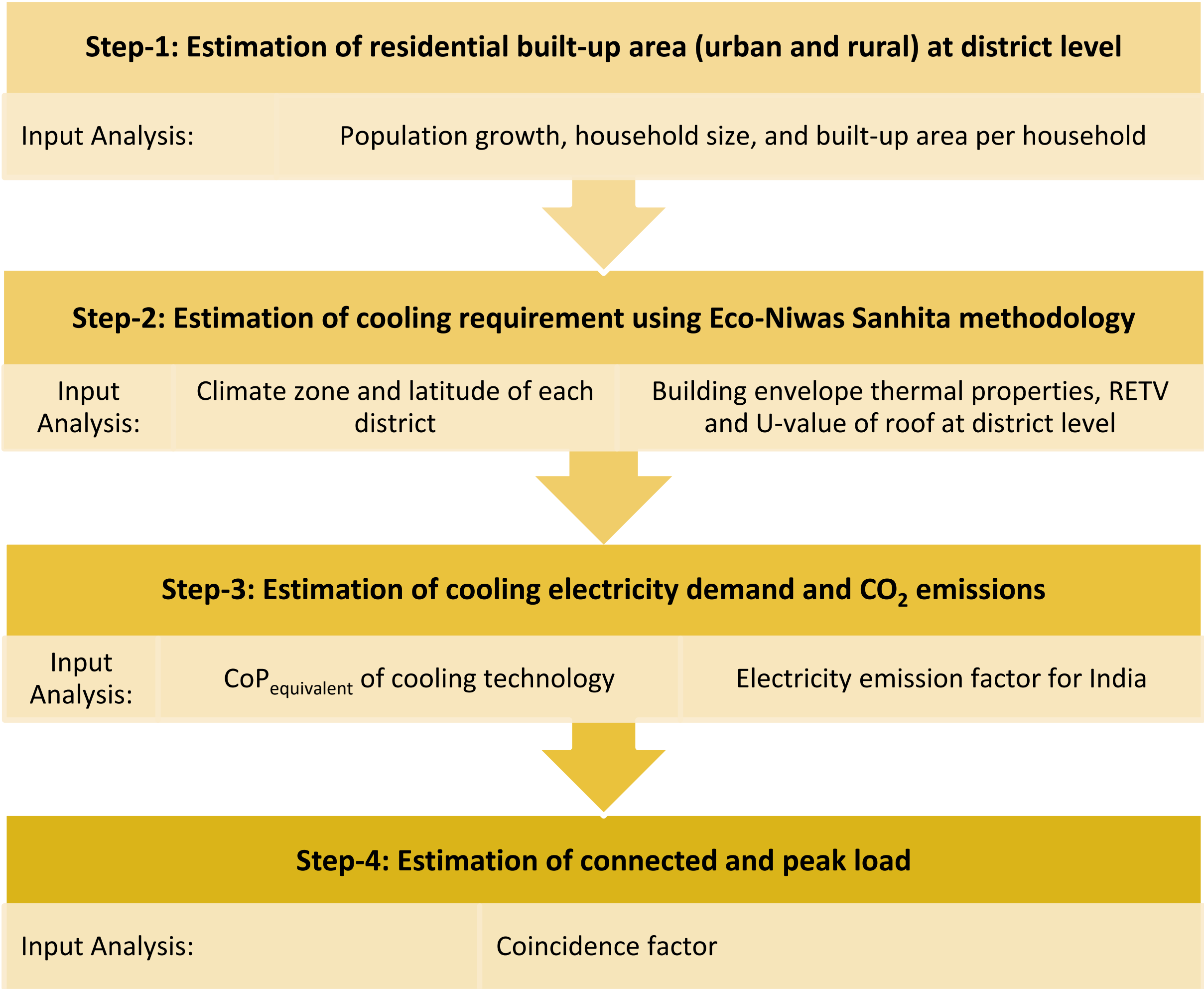


Figure 3: Overall modelling methodology

2.1.1 Estimation of residential built-up area (urban and rural) at the district level

- Projection of population and the number of households in urban and rural areas of each district: Based on the district-wise population and the number of households data from census 2001 and 2011, and projections of country's population available for 2050 (IESS, 2015), the district-wise population and the number of households are projected until 2050. The number of households in urban and rural areas is also projected for each district based on the urbanization trend.
- Projection of urban residential built-up area is done as follows:
  - NSSO 2008 provides data on state-wise average built-up area per household during 2006–2007. The same data is assumed as the average built-up area per household for the year 2011 also (Ministry of Statistics and Programme Implementation, 2008).
  - The average residential area per capita versus GDP per capita (PPP) has been plotted for different countries by IEA (Figure 4). It is observed that though all countries show an increase in average residential area per capita with GDP growth, China shows high average floor space (~40 m^2/person) at the per capita GDP of around USD 20,000, while Mexico, at similar per capita GDP, shows a smaller average floor area (~25 m^2/person) and Korea, at almost twice the per capita GDP of China (~USD 40,000), has only around 30 m^2/person.

Some studies[5] project India's per capita GDP (PPP) to reach to around USD 40,000 by 2050. So, the question is whether India will follow Korea or China in terms of floor area per capita growth during the 2020–2050 period. Recent literature on current trends in urban residential housing in India indicates that in the coming decade, a large part of new urban housing in India is to be expected in the form of affordable housing[6] and co-living spaces[7] emerging as preferred option by the younger generation. If both trends persist until 2050, the increase in per capita urban residential floor area will be relatively small. From an environmental sustainability viewpoint also, less resource use in new construction and compact cities are desirable. Considering these trends, we expect only a marginal increase in per capita residential floor area in India.

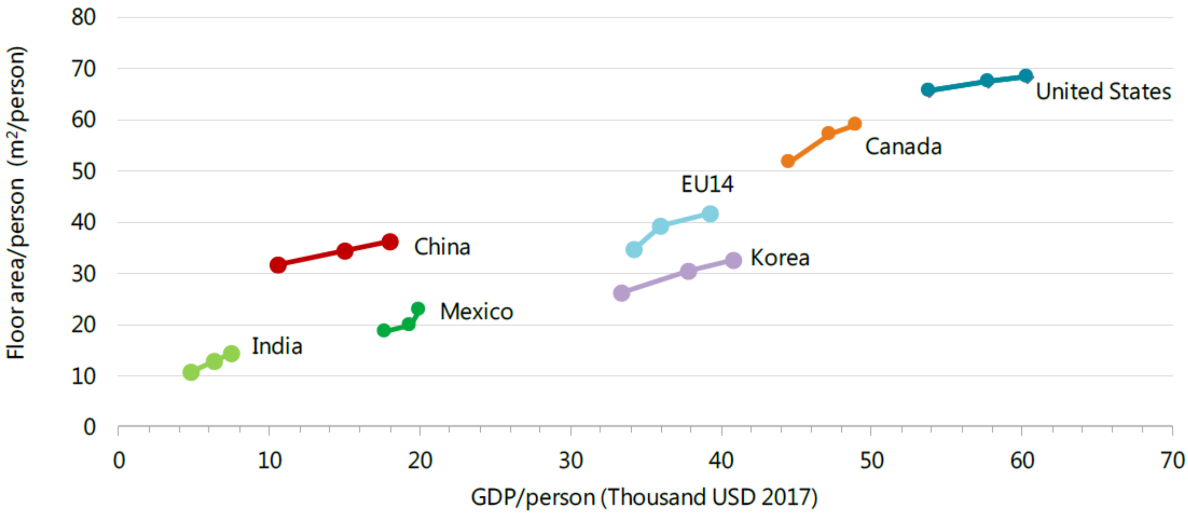


Figure 4: Average residential area per capita versus GDP in selected countries (Source: IEA, 2019).

Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) publishes detailed guidelines on the minimum and recommended (ideal) amount of living space that a person should have to have a 'healthy and culturally fulfilling life'.[8] As per these guidelines, the recommended (ideal) amount of floor space required for a household for leading a fulfilling life with various lifestyle activities is (20 m^2 × no. of people + 15 m^2) in urban areas and (25 m^2 × no. of people + 25 m^2) in rural areas. For our analysis, it has been assumed that by 2050 the average built-up area per household in India will be equal to the Japanese recommended norms. For the intermediate years, i.e. between 2011 and 2050, linear interpolation has been used to calculate the built-up area per household. The assumptions made in our study result in an average urban residential area per capita of 24.2 m^2 in 2050.

- The total built-up area is segregated into existing and newly constructed area for each of the time periods, i.e., 2020–25, 2025–30, 2030–40, and 2040–50. For this, the life of a building is assumed to be 50 years and further that the built-up area existing in 2020 will be demolished at a uniform rate every year until 2070 and will be replaced by new buildings.

[5] https://www.pwc.com/gx/en/issues/economy/the-world-in-2050.html.
[6] https://www.cbre.co.in/en/about/media-centre/cbre-credai-real-estate-in-2030.
[7] http://www.businessworld.in/article/How-Co-Living-Is-Addressing-The-Challenges-Of-India-s-Real-Estate-Space/24-08-2019-175157/.
[8] https://resources.realestate.co.jp/living/how-much-living-space-does-the-average-household-have-in-japan/.

This segregation helps us in developing different strategies for improving building envelope properties of existing and new buildings.

2.1.2 Estimation of space cooling requirement using Eco-Niwas Samhita (ENS) methodology

Eco-Niwas Samhita (Part I) 2018 or the Energy Conservation Building Code for Residential Buildings (ECBC-R) was launched by the Bureau of Energy Efficiency in December 2018. The key features of the code are explained in Box 1. The ENS methodology is the basis for estimating space cooling requirement in this study.

Box 1: Eco-Niwas Samhita

Eco-Niwas Samhita (2018) or ECBC-R has the following provisions (BEE 2018):

1. To minimize the heat gain in cooling-dominated climate or heat loss in heating-dominated climate:
   a) Through the building envelope (excluding roof):
      i) Maximum Residential Envelope Transmittance Value (RETV)[9] for cooling-dominated climate (composite climate, hot-dry climate, warm-humid climate, and temperate climate)
      ii) Maximum U-value for the cold climate
   b) Through the roof: Maximum U-value for roof
2. For natural ventilation potential:
   a) Minimum openable window-to-floor area ratio with respect to the climatic zone
3. For daylight potential:
   a) Minimum visible light transmittance with respect to window-to-wall ratio.

RETV gives a quantitative measure of heat gains through the building envelope (excluding roof). Energy simulations were done with various combinations of inputs (floor plan, climate, and building envelope) to calculate RETV. RETV formulation was done with the key building envelope parameters and coefficients. The coefficients of the RETV formula were derived using multiple linear regression analysis to minimize the error between the simulated RETV and calculated RETV. During the development of ENS 2018, a setpoint temperature of 26 °C was taken, and this study also follows the same.

[9] Residential envelope transmittance value (RETV) (W/m^2) is the net heat gain rate (over the cooling period) through the building envelope (excluding roof) of the dwelling units divided by the area of the building envelope (excluding roof) of the dwelling units.

- The space cooling requirement depends primarily on the climate and also on the latitude. A state-wise list of all the districts as per the 2011 census and their respective climatic zone[10] and latitude (≥ 23.5°N or < 23.5°N) was prepared.
- U-value of wall and roof: Census provides information on the distribution of the number of households according to the materials used for wall and roof construction at the district level. This data from Census 2011 is used to estimate the weighted average U-value of wall and roof for each district, and it is assumed that these will remain same for the base year 2020. The U-value of wall is used to estimate the RETV, whereas the U-value of roof is used to estimate heat gains through the roof. Other key envelope parameters such as the window area, window glass properties, and window shading are kept same for all districts.
- Cooled area: 70% of the total built-up area is considered for estimating the space cooling requirement, assuming that only 70% of the built-up area of each household needs to be cooled (excluding kitchen and toilet areas) for providing thermal comfort.
- Estimation of space cooling requirement: Using RETV, roof heat gains, and the correlations developed based on building simulation results conducted during development of ENS 2018, the thermal energy to be removed to maintain thermal comfort (set temperature of 26 °C) is estimated for the year 2020.
- The target values of RETV and roof U-value for new and existing buildings are set for different time periods under different scenarios for estimating the future space cooling requirement under different scenarios. The various scenarios are explained in Section 2.1.5.

2.1.3 Estimation of cooling electricity demand and CO_2 emission

- Estimation of cooling electricity demand in different scenarios: The equivalent coefficient of performance ($CoP_{equivalent}$) of cooling appliances is taken as 2.75 for the base year 2020 (IESS, 2015), and target values are set under different scenarios (Section 2.1.5) to estimate the cooling energy demand.
- Estimation of CO_2 emission: This is done by multiplying the cooling electricity demand with the emission factor (0.82 kg of CO_2/kWh) (Central Electricity Authority, 2018). The emission factor is assumed to remain constant for the 2020–50 period.

2.1.4 Estimation of connected and peak load

- Estimation of connected load:
  - It is assumed that a typical 12 × 12 ft or 144 sq. ft area will be fitted with a 1.5 TR air conditioner. Considering this norm and the area to be cooled, the cooling capacity (thermal) of the cooling system is calculated for 2020.
  - Connected load is calculated by dividing the cooling capacity (thermal) of the cooling system with the $COP_{equivalent}$.

  For future projection of the connected load, improvements in the building envelope thermal properties as well as improvements in $CoP_{effective}$ are considered.

[10] India is divided into five climatic zones as per the National Building Code and the same climate classification is used in this study.

- Estimation of peak load: It is calculated by multiplying the connected load with the coincidence factor.[11] In the current analysis, the coincidence factor is assumed to be 0.70.

2.1.5 Scenarios

The cooling electricity demand of a building depends on two factors:

a) Building envelope properties, which are characterized by two parameters: RETV and roof U-value

b) Efficiency of the cooling technology employed, characterized by the equivalent coefficient of performance ($CoP_{equivalent}$)

For projecting the future cooling electricity demand until 2050, two scenarios are considered:

- Business-as-usual (BAU) scenario, which assumes that in the absence of any additional measures, the improvements in building envelope technologies (RETV and roof U-value) and cooling technologies ($CoP_{equivalent}$) will follow BAU trends.
- Deep-cut scenario, in which aggressive measures (beyond BAU) will be taken for improvements in building envelope technologies (RETV and roof U-value) and cooling technologies ($CoP_{equivalent}$) to achieve a deep cut in the cooling energy demand.

The target values set for building envelope and cooling technology parameters under the two scenarios are discussed in the following sections.

2.1.5.1 Envelope technologies

The target values of RETV and roof U-value set for new and existing buildings during different time periods until 2050 under the two scenarios are provided in Table 7. It also mentions the percentage built-up area (existing or new) to which these values are applied during each time periods.

Table 7: Target values for envelope parameters under BAU and deep-cut scenarios

			Time period			
			2020–25	**2025–30**	**2030–40**	**2040–50**
BAU scenario	Existing buildings	RETV (W/m²)	No improvement	No improvement	No improvement	No improvement
		Percentage of built-up area (existing) applied	100%	100%	100%	100%
		Roof U-value (W/m².K)	No improvement	No improvement	No improvement	No improvement
		Percentage of built-up area (Existing) applied	100%	100%	100%	100%
	New buildings	RETV (W/m²)	15	15	15	15
		Percentage of built-up area (new) applied	10%	25%	50%	50%
		Roof U-value (W/m².K)	1.2	1.2	1.2	1.2
		Percentage of built-up area (new) applied	10%	25%	50%	50%
Deep-	Existing	RETV (W/m²)	15	15	12	12

[11] *Coincidence factor* is the peak of a system divided by the sum of peak loads of its individual components. It tells how likely the individual components are peaking at the same time. http://blog.drhongtao.com/2014/11/load-factor-coincidence-factor-diversity-factor-responsibility-factor.html.

cut scenario	buildings	Percentage of built-up area (existing) applied	10%	40%	60%	80%
		Roof U-value (W/m^2.K)	1.2	1.2	1	1
		Percentage of built-up area (existing) applied	10%	40%	60%	80%
	New buildings	RETV (W/m^2)	15	12	8	8
		Percentage of built-up area (new) applied	75%	75%	75%	100%
		Roof U-value (W/m^2.K)	1.2	1	0.5	0.5
		Percentage of built-up area (new) applied	75	75	75	100

BAU Scenario:

This scenario assumes slow implementation of ENS (a period of 10 years is assumed for it to become mandatory in all states and urban areas) and a slow expansion of market for efficient building materials and components, e.g., AAC blocks/hollow clay blocks and roof insulation. As ENS 2018 is applicable to residential buildings constructed on a plot size of ≥500 m^2, a large part (≥50%) of the residential construction is assumed to remain outside the purview of ENS 2018. Further, it assumes no update of ENS 2018 during 2020–50. The penetration of residential buildings complying with RETV and U_{roof} criteria (i.e., RETV = 15 W/m^2 and U_{roof} = 1.2 W/m^2.K) increases from 10% (2020–25) to 25% (2025–30) and 50% (2030–50).

It assumes no policy action taken to retrofit existing residential building stock and hence no improvement in the RETV of existing residential buildings during the entire 2020–50 time period.

Deep-cut Scenario:

ENS implementation is taken up in a mission mode by the Government of India. ENS compliance becomes part of the Prime Minister's Awas Yojana (PMAY) (Urban) and is integrated into model building bye-laws. Political support is provided at the highest level, so all states will start complying with ENS within the next 2–3 years. The cut-off of 500 m^2 plot area is reduced to bring in large number of residential buildings under the purview. ENS is updated every 5 years and is progressively made more stringent.

A market transformation programme (consisting of labelling, industrial support, procurement, etc.) to transform the market for walling materials (insulating blocks), roof insulation solutions, and external movable shading systems is launched.

A programme on applied R&D and commercialization of next-generation building materials and components is launched, resulting in fast commercial availability at affordable new-generation materials (e.g., aerogel-based plasters and external movable shading systems).

A programme to retrofit existing residential buildings will be started during 2020–25 and expanded aggressively in later years.

The following assumptions are also made:

- New buildings: The RETV cut-off will be progressively made more stringent: RETV = 15 W/m^2 (2020–25), RETV = 12 W/m^2 (2025–30), RETV = 8 W/m^2 (2030–50). Similarly, U_{roof} will be progressively made more stringent: U_{roof} = 1.2 W/m^2.K (2020–25), U_{roof} = 1 W/m^2.K (2025–30), U_{roof} = 0.5 W/m^2.K (2030–50). The percentage of built-up area (new) complying with ENS would increase from 75% (2020–40) to 100% (2040–50).

- Existing buildings: The RETV and U_{roof} of 10% of the existing built-up area will improve to 15 W/m^2 and 1.2 W/m^2.K, respectively, during 2020–25; those of 40% of the existing built-up area to 15 W/m^2 and 1.2 W/m^2.K, respectively, during 2025–30; those of 60% of the existing built-up area to 12 W/m^2 and 1 W/m^2.K, respectively, during 2030–2040, and those of 80% of the existing built-up area to 12 W/m^2 and 1 W/m^2.K, respectively, during 2040–50.

2.1.5.2 Cooling Technologies

The target values for the average equivalent efficiency of cooling technologies under the two scenarios are provided in Table 8.

Table 8: Target values for cooling technology efficiency under BAU and deep-cut scenarios

	$CoP_{equivalent}$				
	2020	**2025**	**2030**	**2040**	**2050**
BAU scenario	2.75	3.13	3.50	4.25	5.00
Deep-cut scenario	2.75	3.55	4.34	5.93	7.52

BAU Scenario

Under the BAU scenario, it is expected that the average equivalent efficiency of cooling technology will increase at a uniform rate of 2% per annum because of the existing measures, so by 2050 the $CoP_{equivalent}$ will be 5.

Deep-cut Scenario

Under the deep-cut scenario, it is assumed that the average $CoP_{equivalent}$ will become 7.52, which is the CoP of the most efficient RAC available in the global market (Korean cooling-season performance factor [CSPF] of 9.4, which is about 15%–20% lower when converted to Indian Seasonal Energy Efficiency Ratio [ISEER]) (Abhyankar et al., 2017).

2.2 Results

2.2.1 Residential built-up area

The projected increase in urban and rural residential built-up area is plotted in Figure 5.

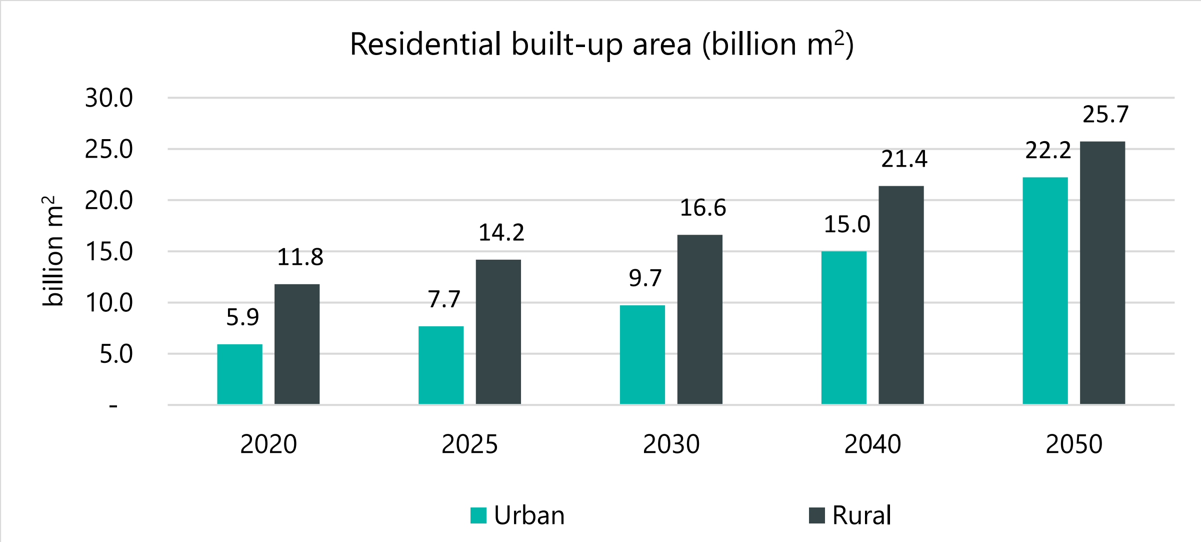


Figure 5: Projection of total urban and rural residential built-up area

The total urban residential built-up area will increase from 5.9 billion m^2 (2020) to 22.2 billion m^2 (2050) and the rural built-up area from 11.8 billion m^2 (2020) to 25.7 billion m^2 (2050). The per capita residential built-up area in urban area will increase from 12.6 m^2 (2020) to 24.2 m^2 (2050).

2.2.2 Space cooling requirement

The space cooling requirement or estimation of the amount of thermal energy that needs to be removed to maintain thermal comfort (dependent upon the building envelope properties) for the entire residential building stock (urban and rural) for 2020–50 is presented in Figure 6. The total space cooling requirement for residential buildings in 2020 is estimated at 2991 TWh_{th}/year, out of which 30% is contributed by urban residential buildings and 70% by rural residential buildings. This requirement increases to 6840 TWh_{th}/year by the year 2050, with the contribution of urban residential buildings increasing to 42%.

As this study focuses on the urban residential building sector, from now on only the results relevant to urban residential sector are presented and discussed.

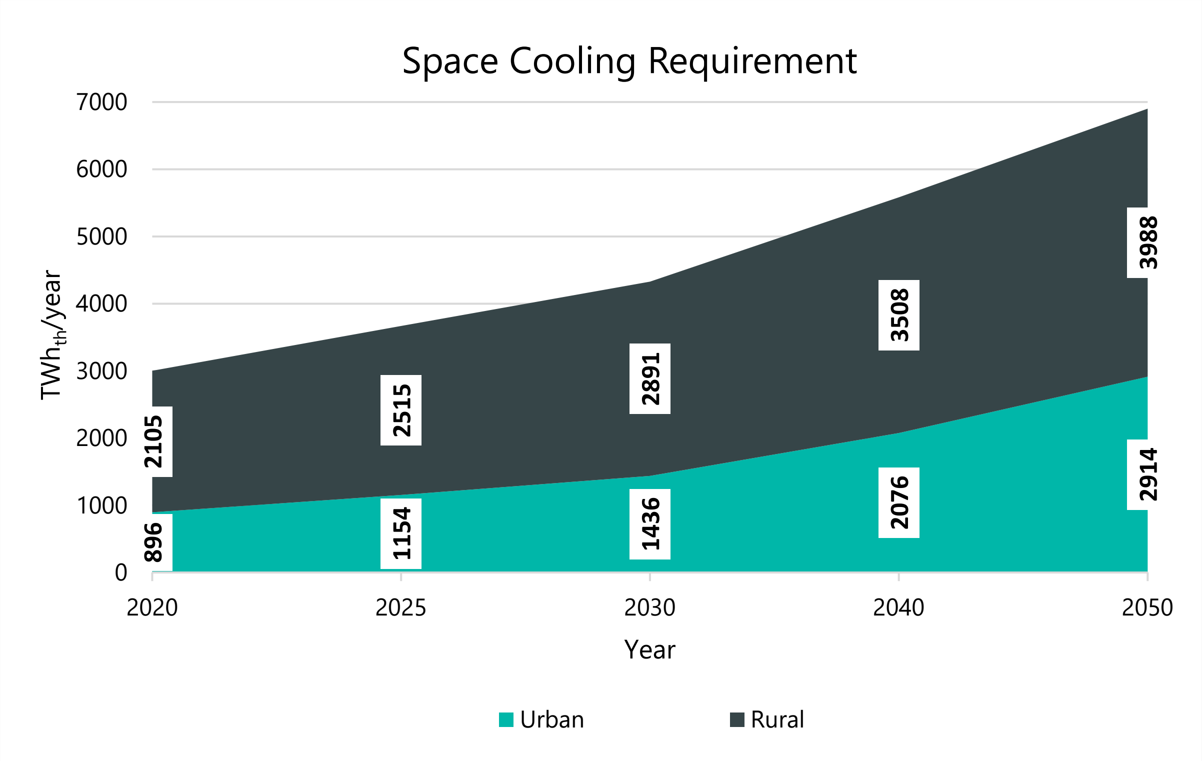


Figure 6: Space cooling requirement for the residential sector (urban + rural)

The space cooling requirement for urban residential buildings under the two scenarios are plotted in Figure 7.

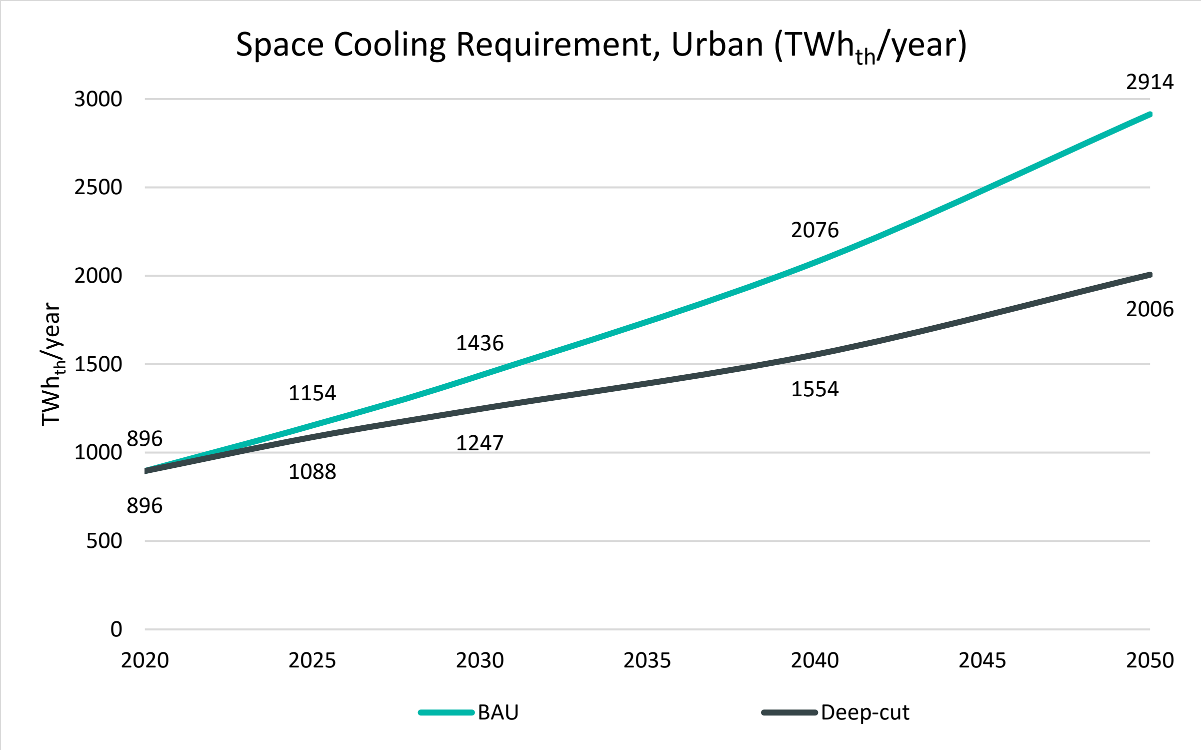


Figure 7: Space cooling requirement for urban residential sector

The space cooling requirement for urban residential buildings for providing thermal comfort for all is expected to increase from 896 TWh$_{th}$/year in 2020 to 2914 TWh$_{th}$/year in 2050 in the BAU scenario. Improvement in building envelope properties as per the deep-cut scenario can help in reducing the space cooling requirement from 2914 TWh$_{th}$/y to 2006 TWh$_{th}$/year in the year 2050, which is 30% lower compared to that of BAU. The space cooling requirement for urban residential buildings for different states of India for 2050 under BAU and deep-cut scenarios is shown in Figure 8.

Deep-cut scenario takes into account improvements in both existing buildings and new buildings. While new buildings have major potential for energy savings, retrofit in existing buildings also have significant potential. The analysis shows that for the year 2030, the saving potential (deep-cut scenario as compared to BAU scenario) in cooling energy requirement for urban residential buildings is 189 TWh$_{th}$/year. Out of this saving potential, 40 TWh$_{th}$/year or 21% of the total saving potential will come from the retrofit of existing buildings.

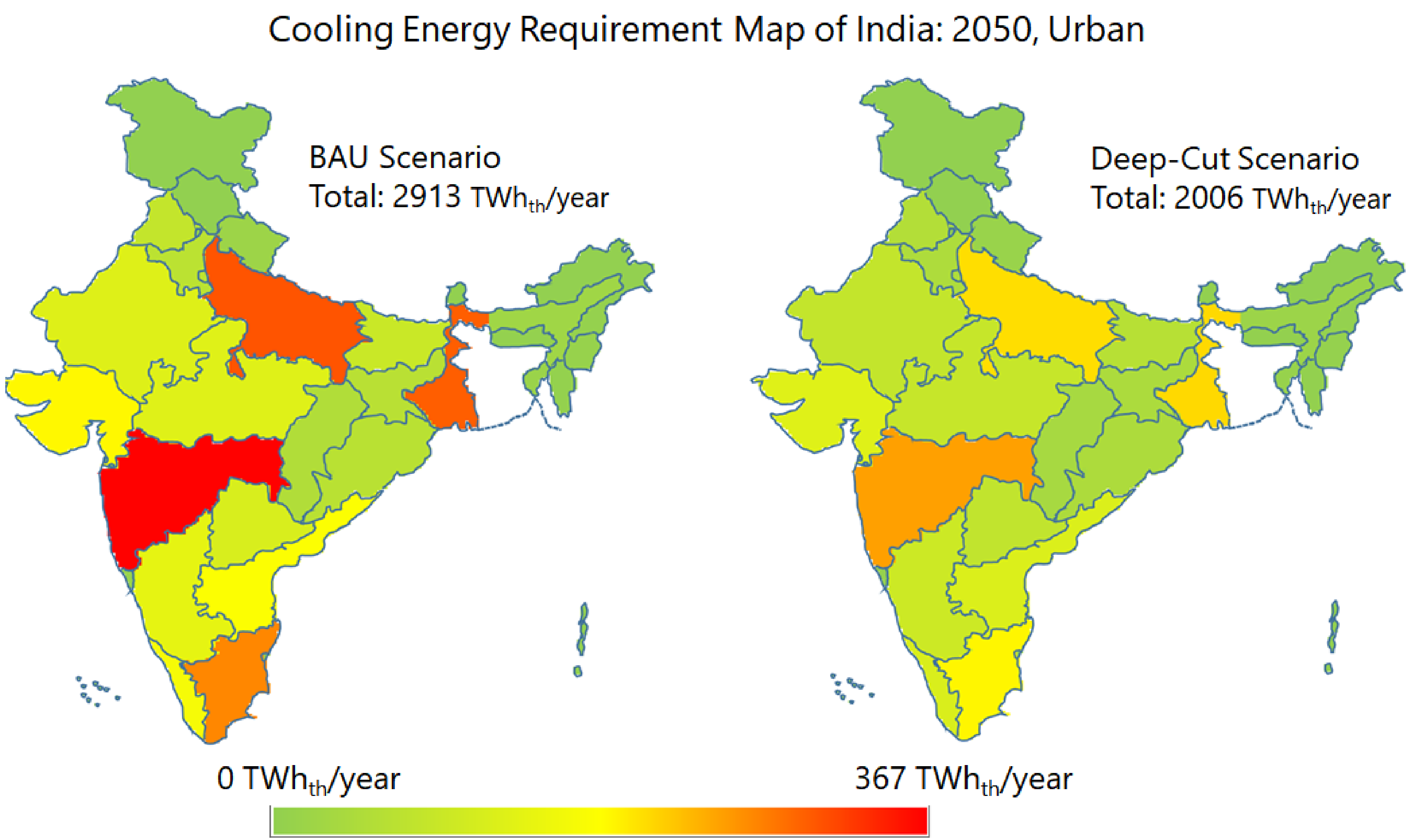


Figure 8: Space cooling requirement map of India for residential urban sector (2050) under different scenario.

2.2.3 Cooling electricity demand and CO_2 emission

The estimated cooling electricity demand under various scenarios is plotted in Figure 9.

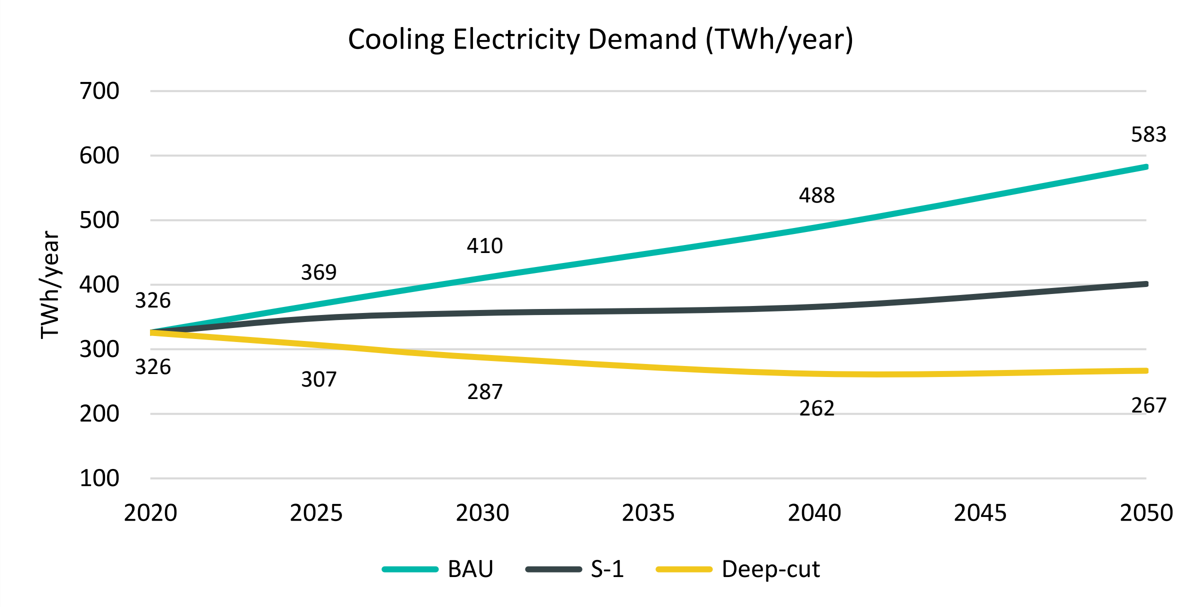


Figure 9: Estimated cooling electricity demand under various scenarios

The cases presented in Figure 9 are explained below:

Case	Envelope parameters	Cooling technology efficiency
BAU	BAU scenario	BAU scenario
S-1 **(shows only the impact of deep-cut envelope measures)**	Deep-cut scenario	BAU scenario
Deep-cut **(shows the impact of both envelope and cooling technology measures)**	Deep-cut scenario	Deep-cut scenario

The cooling electricity demand for providing thermal comfort for all in urban residential buildings is estimated at 326 TWh/year for the year 2020, which is almost 3.5 times the current electricity consumption for RACs (around 90 TWh/year). Under the BAU scenario, it is expected that the cooling electricity demand will increase to 583 TWh/year in 2050. Through improvement in both building envelope and cooling technologies according to the deep-cut scenario, the cooling demand can be reduced to 267 TWh/year in 2050, which is almost 55% less than that in the BAU scenario.

Under the deep-cut scenario, energy saving of 316 TWh/year is possible compared to the BAU scenario for the year 2050, which is equivalent to 259 million tonnes of CO_2 emissions reduction per year.

2.2.4 Connected and peak load

Assuming thermal comfort for all, the connected load for the cooling system would increase to 1031 GW in 2050, as compared to 577 GW in 2020, under the BAU scenario. Under the deep-cut scenario, the connected load for the cooling system would reduce to 472 GW in 2050, resulting in a reduction of 55% compared to the BAU scenario.

Considering a coincidence factor of 70% (Abhyankar et al., 2017), the peak load for the cooling system would increase to 722 GW in 2050 compared to 404 GW in 2020 under the BAU scenario. Under the deep-cut scenario, the peak load for the cooling system would reduce to 330 GW in 2050, resulting in a reduction of 55% compared to the BAU scenario (Figure 10). This translates to a minimum 391 GW of avoidable power generation capacity addition, which is equivalent to a savings in investment of INR 15,65,000 crore on power plants (considering investment of INR 4 crore/MW)

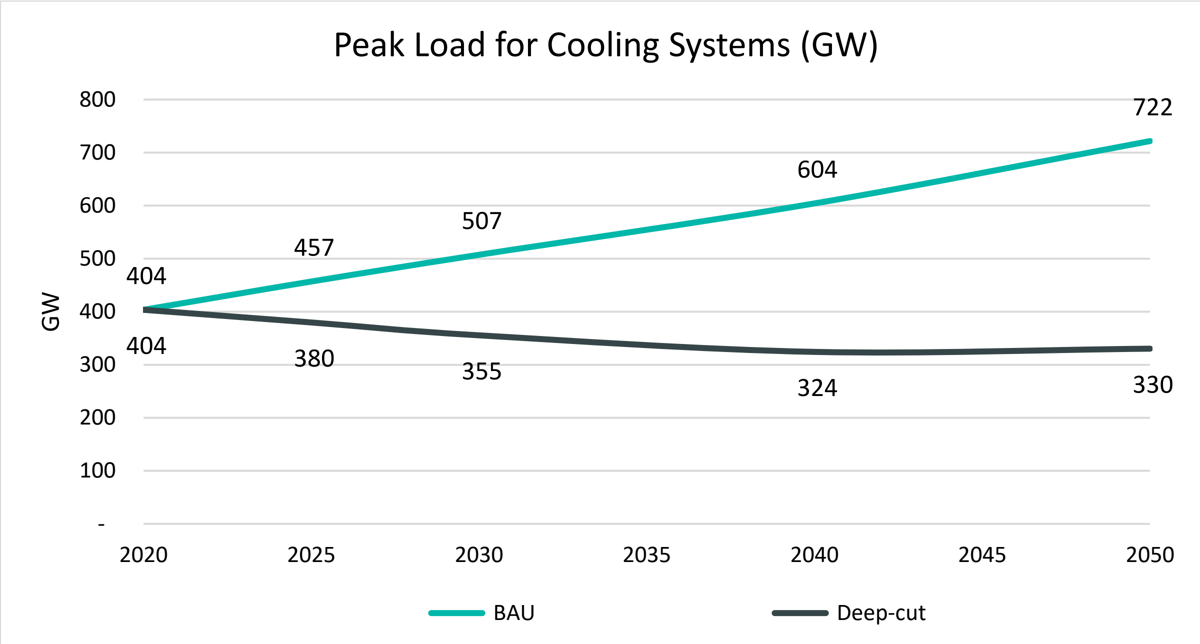


Figure 10: Estimated peak load for cooling system under different scenarios

2.2.5 Impact of increased setpoint temperature

The thermal comfort condition used for estimation of cooling energy demand is based on a set temperature of 26 ˚C. If the set temperature is increased to 28 ˚C, the cooling electricity demand can be further reduced by 12% (Figure 11).

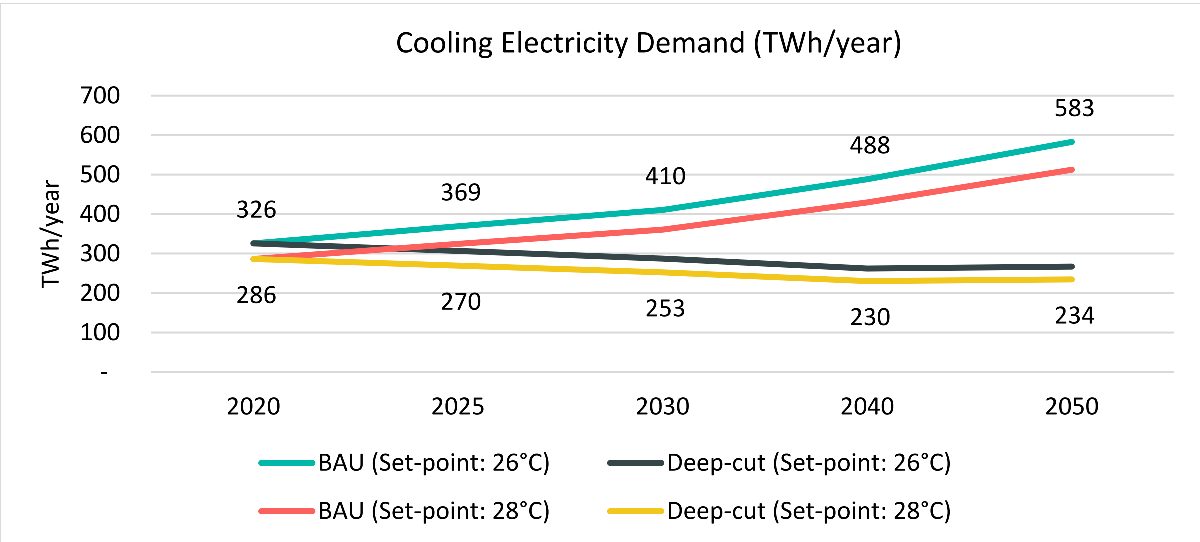


Figure 11: Impact of increased setpoint temperature on cooling electricity demand

2.2.6 Impact of retrofitting existing buildings

Under the deep-cut scenario, a marginal improvement in the envelope of existing buildings through retrofits brings in significant savings. Our analysis shows that for the year 2030, out of the total reduction of 189 TWh_{th}/year in space cooling requirement in the deep-cut scenario compared to BAU scenario, almost 40 TWh_{th}/year or 21% of the reduction comes from the retrofit of existing buildings.

2.3 Discussion points

2.3.1 Importance of building envelope

To cool any enclosed space, heat needs to be removed from that space. Heat ingress in the space happens from external sources (heat gains through external walls, windows, roof, etc. due to solar radiation and high outside temperature) and internal sources (occupants, lighting, appliances, etc.). Residential buildings are externally heat-load dominated, which means that a major part (>70%, excluding the heat generated from cooking) of the heat comes from external sources. Hence, the building envelope (consisting of external walls, windows, and roof) becomes the most important element affecting the space cooling requirement in a residential building.

2.3.2 Building retrofits

Until now, in India the focus of building energy efficiency programmes has been on new buildings. Building envelope retrofit options are generally limited and the costs are high compared to incorporating similar features in the construction of new buildings. However, results of our study indicate that given the large existing residential building stock and significant potential to reduce space cooling requirements, retrofitting of existing buildings also needs focused attention.

2.3.3 Impact of building envelope on thermal comfort

Thermal comfort is the condition of thermal environment under which a person can maintain a body heat balance at normal body temperature and without perceptible sweating (BIS, 2016). A thermal comfort model is developed for India, which is known as 'India Model for Adaptive Thermal Comfort (IMAC)'. IMAC models for neutral temperatures and acceptability limits for air conditioned, naturally ventilated, and mixed-mode buildings, as derived through an empirical field study specific to the Indian context. It defines a temperature band within which the space can be considered as thermally comfortable.

Discomfort degree hour (DDH) is calculated for naturally ventilated spaces for the cooling period based on IMAC, which is the summation of differences of hourly operative temperature and IMAC band maximum temperature, only for hours when the temperature goes outside the IMAC temperature band with 90% acceptability. If DDH is lower, then the space is thermally more comfortable.

To understand the impact of building envelope on thermal comfort, the results (Figure 12) are shown for two locations (New Delhi and Mumbai). The building envelope is characterized by RETV and thermal comfort by DDH. The RETV values are taken as 18.5 W/m^2 (average RETV of present building stock) and 8 W/m^2 (RETV value considered for new buildings under deep-cut scenario).

Natural ventilation has been considered for both the cases, i.e., the windows are opened if the outside air is cooler than the inside space.

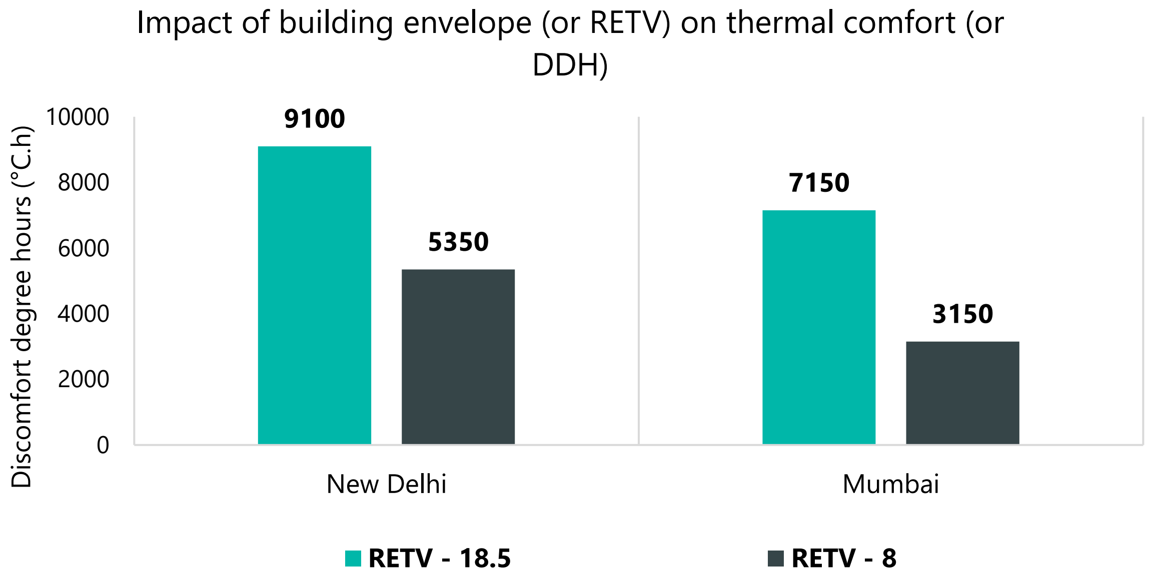


Figure 12: Impact of building envelope (or RETV) on thermal comfort (or DDH)

The results show that the DDH reduces by 41% in Delhi and by 56% for Mumbai if the RETV is reduced from 18.5 to 8 W/m^2. If the building remains unconditioned, then a lower RETV helps to substantially improve (in the same order of improvement in DDH) the thermal comfort. If the building is air-conditioned, then the operational time for the air conditioner is reduced and, in addition, the energy required by the air conditioner during the operational hours is also reduced, resulting in, overall, a substantial reduction in the energy required for cooling.

2.3.4 Costs

The typical construction costs for various envelope options that have been modelled (having different RETV and U_{roof} values) are presented in Table 9. It is observed that the incremental cost for complying with the requirements of the Eco-Niwas Samhita entails only a very small (+1.2%) increase in the construction cost. Only when the building envelope specifications are made more stringent (RETV = 8 W/m^2, U_{roof} = 0.5 W/m^2.K), which the code provision is projected to have after 2030 under the deep-cut scenario, that the incremental cost is higher (+9.2%) at the current prices. The construction cost calculations are based on the Central Public Works Department (CPWD) schedule of rates for Delhi and data collected from the market.

Table 9: Construction cost for different building specifications

Building envelope specification	**Building envelope construction details**	**Average basic construction cost (excluding electrical fittings, furnishing, painting, etc.)**	**Percentage increase over the BAU case**
1. BAU construction **RETV = 18.5 W/m²** U_{roof} **= 2.5 W/m².K**	• 230-mm burnt clay brick wall with plaster • Single-glazed window with aluminum frame • Minimum fixed shading • Concrete slab with standard finish • Window-to-wall ratio = 15%	INR 12,900/m²	0
2. Complying with RETV and U_{roof} **provisions of Eco-Niwas Samhita** **RETV = 15 W/m²** U_{roof} **= 1.2 W/m².K**	• 200-mm AAC/hollow clay block wall with plaster • Single-glazed window with aluminum frame • Minimum fixed shading • Concrete slab with 25-mm insulation with standard finish • Window-to-wall ratio = 15%	INR 13,060/m²	+1.2%
3. RETV =12 W/m² U_{roof} **= 1.0 W/m².K**	• 200-mm AAC/hollow clay block wall with plaster • Single-glazed window with aluminum frame • Optimized fixed shading • Concrete slab with 25-mm insulation with standard finish • Window-to-wall ratio = 15%	INR 13,110/m²	+1.6%
4. **RETV = 8 W/m²** U_{roof} **= 0.5 W/m².K**	• Clay brick cavity wall with sandwich insulation • Double-glazed window with uPVC frame • Optimized fixed shading • Concrete slab with 50-mm insulation with standard finish • Window-to-wall ratio = 15%	INR 14,085/m²	+9.2%

2.3.5 Comparison of results with other studies

Results from this study were compared with those of the six studies covered in Chapter 1 (Figure 13).

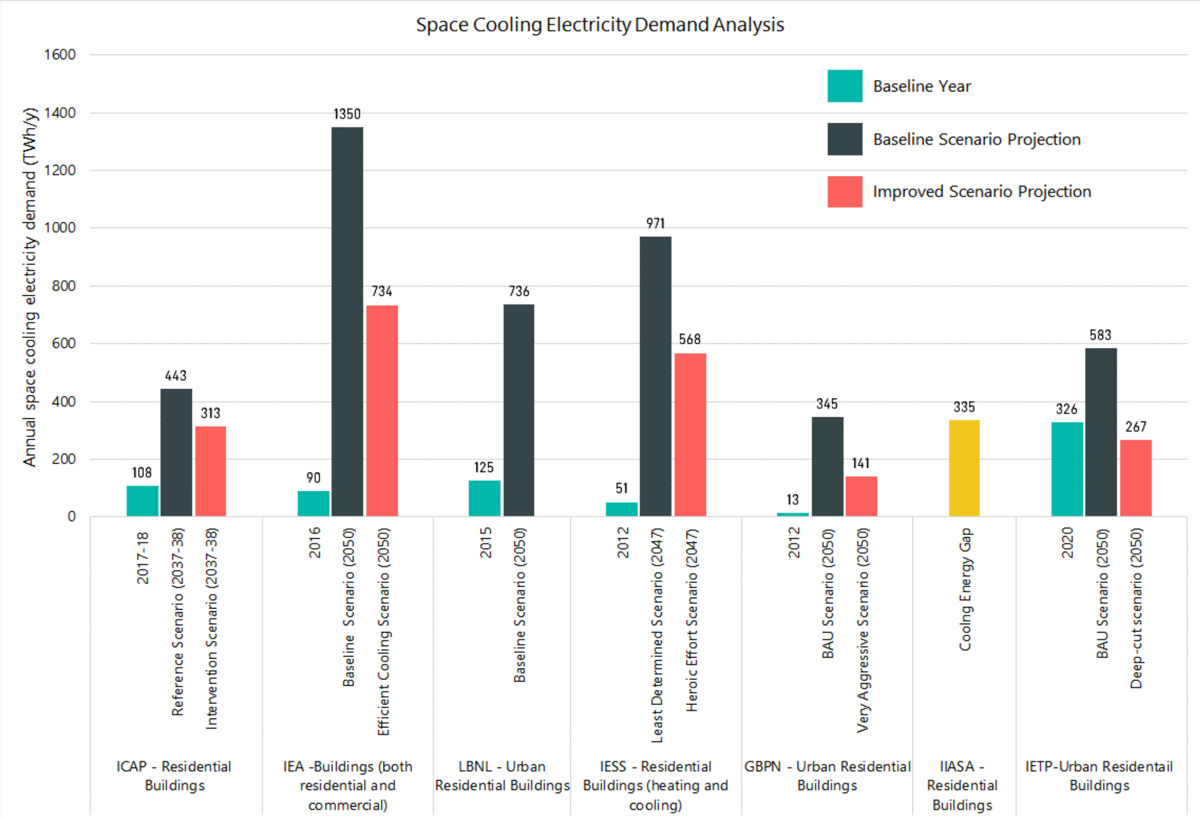


Figure 13: Comparison of results with other studies

The studies have different objectives, assumptions, residential sector descriptions (urban/rural), and scenario timelines, which makes the comparison difficult. However, broadly the following observations are evident:

- ICAP figures for 2017/18 are nearly one-third of the space cooling electricity demand for 2020 estimated in this study. This reflects the cooling gap currently existing in the country, as this analysis includes the cooling energy requirements of all urban households to achieve thermal comfort. If the cooling energy requirement of rural households is added, this gap would be even larger.
- Similarly, the 2050 BAU scenario is significantly higher for just urban residential buildings compared to the ICAP assessment, which estimates that only 40% of the population in 2037/38 will have the means to access cooling technologies.
- The LBNL study, which models a non-linear growth pattern for India's space cooling demand based on China's experience in the last 35 years, estimates a much higher cooling demand at 736 TWh/year. This highlights the need to not underestimate the likely cooling demand based on incremental growth scenarios alone.
- Finally, the analysis shows that in the deep-cut scenario, a saving of around 54% is possible if both efficient envelope and cooling technologies are given priority, as compared to studies where only technology options are considered.

3 Assessment of Technologies

It was shown in Chapter 2 that through improvement in building envelope properties as per the deep-cut scenario, the amount of thermal energy required to be removed can be reduced by 30% compared to the BAU case. Through improvement in both building envelope and cooling technologies as per the deep-cut scenario, almost 55% reduction in cooling electricity demand is possible by 2050 as compared to BAU case. This chapter provides a review and assessment of building envelope and cooling energy technologies that can help in achieving these reductions.

3.1 Approach

The methodology for assessment of technologies consists of four steps (Figure 14):

- Listing of envelope and cooling technologies through literature review and market information.
- Mapping of the technology readiness level (TRL) for technologies.

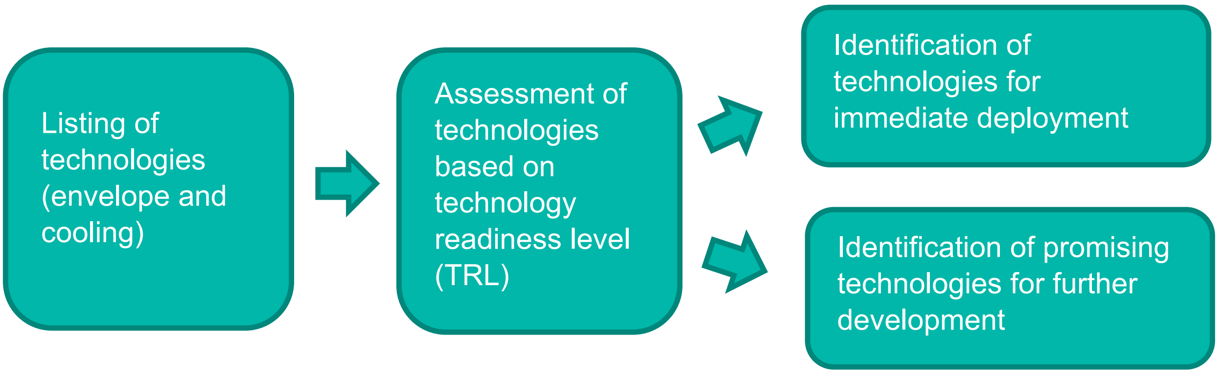


Figure 14: Methodology for the assessment of technologies

3.2 Building envelope technologies

3.2.1 Technologies available for immediate deployment

There are several products/technologies commercially available in the market that can help in reducing heat gains from the building envelope. A list of selected products/technologies having high scaling potential is provided in Table 10. A suitable combination of technologies/products for walls, roof, and windows (see Table 9) can help in achieving a lower RETV and U_{roof} as proposed under the deep-cut scenario. All these products currently have a low market share and face common barriers, such as low awareness, limited accessibility, small manufacturing base, not fully developed supply chains, small pool of trained applicators/technicians, and in some cases higher costs.

Table 10: Building envelope technologies available for immediate deployment

Building product/ technology	Example	Application	Accessibility	Affordability
Bricks/blocks with low thermal conductivity	Autoclaved aerated concrete (AAC) blocks, hollow clay blocks, cellular lightweight concrete (CLC) blocks, etc.	Majority of the house construction in India is masonry construction and these bricks/blocks can help in reducing conduction heat gains from walls in new construction	Small manufacturing base, supply chain limited to metros/large cities in certain regions	Cost of construction is comparable to traditional bricks
High-performance windows	Double-glazed window units	Will help in reducing conduction heat gains from windows. Can be applied to new buildings and during major retrofits of existing buildings	Supply chain limited to metros/large cities	High initial cost. Affordability is a concern
External movable shading products	Roller blinds, vertical louver systems, bamboo chicks, lamella blinds, etc.	Will help in reducing direct solar heat gains from windows. Can be applied to both new and existing buildings. Some of the systems can be easy to retrofit	Bamboo chicks are widely available but limited availability of other products and small manufacturing base. Marked demand for a larger variety and better-quality products	Bamboo chicks are low cost; other products have higher costs
Ready-to-use finished insulation products	Glass wool, mineral wool, expanded polystyrene (EPS)	Will reduce conduction heat gains from walls and roofs	Supply chain limited to metros/large cities. Small number of trained applicators	High initial cost. Affordability is a concern
Roof tiles with low thermal conductivity and/or high solar reflectance index (SRI)	Hollow clay roofing tile, expanded clay roofing tile, cool roof tiles	Will reduce conduction heat gains from roofs. These are easy to apply, though careful selection is required. Can be used for both new and existing	Small manufacturing base, supply chain limited to metros/large cities in certain regions	Additional cost

		buildings		
Construction technologies	Insulating concrete forms (ICF) and monolithic insulated concrete systems (MICS), various types of expanded polystyrene (EPS) panel system, Aerocon panels	Application limited to new mass housing projects in the organized sector	Limited number of construction companies capable of undertaking these	High initial cost. Affordability is a concern.
Liquid spray foam	Polyurethane foam	Can be highly effective if applied properly. It can be used for both new and existing buildings	Requires specialized equipment and trained manpower for application. Very few applicators	High initial cost. Affordability is a concern

3.2.2 Promising technologies requiring further development

The following reports and papers were reviewed to prepare a list of promising building envelope technologies:

1. IEA and UNEP (2018): 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector. Global Alliance for Buildings and Construction.
2. DoE (2012): Buildings R&D Breakthroughs – Technologies and Products Supported by the Building Technologies Program, U.S. Department of Energy.
3. LBNL (2009): High Performance Building Façade Solutions. PIER Final Project Report, Lawrence Berkeley National Laboratory.
4. REEEM (2019): Innovation Readiness Level Report: Energy Efficiency in Buildings. REEEM project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739.

Based on the literature review, a few promising technologies are presented in Table 11.

Table 11: Promising technologies requiring further development

Building product/ technology	Example	Application	Remarks
Radiative cooling film	Film made of hybrid glass microsphere-plastic[12]	Application on roof to reduce heat gains and increase heat rejection	Radiative cooling films potentially can have large application in existing buildings
Aerogel-based products	External insulating render, internal	Aerogel is a synthetic, porous, ultra-light material	Potential application for retrofitting existing

[12] https://www.colorado.edu/today/2018/10/26/engineers-scale-low-cost-energy-saving-cooling-system.

	insulating plaster, insulated clay bricks[13]	having very low conductivity. Aerogel-based products can be used for reducing heat gains from walls and roofs	buildings, wherein a thin layer of plaster having aerogel can improve the insulation properties of the wall significantly
Smart windows	Suspended particle devices, liquid crystal devices, thermochromic, gasochromic, electrochromic (Sibilio et al., 2018) materials	Thermal and optical properties of the glazing can be varied to control heat gains and control daylight through windows	Potential application in new construction or major renovation.
Phase-change-material (PCM)-based products	Organic (e.g., paraffin or non-paraffin), inorganic (salt or metallic hydrates) or eutectic mixtures obtained from mixing of two or more organic and/or inorganic compounds[14]	PCM integrated with building elements increases the thermal mass and can help in shifting the peak temperatures and reducing energy requirement for cooling	A large part of the literature on analysing PCM material application in buildings consists of theoretical studies, but the number of experimental studies is small. Similarly, there is a lack of economic and environmental studies concerning PCM material applications in buildings

A comprehensive study is needed to access the potential of these technologies and plan a targeted research and development programme leading to commercialization.

3.3 Cooling technologies

3.3.1 Technologies available for immediate deployment

The number of space cooling technologies has advanced in last couple of decades. These cooling technologies can be deployed based on requirement of space. Table 12 summarizes cooling technologies based on their characteristics such as cost, ability to provide indoor environmental conditions, impact on the spatial configuration, etc. Ventilation systems and air motion devices such as fans are also capable of providing thermal comfort; they do not provide cooling but help achieve comfort. They are not covered here.

[13] https://www.wall-ace.eu/the-project/.
[14]https://www.pcm-ral.org/pcm/en/.

Table 12: Cooling technologies and their characteristics

Technology	Impact on the spatial configuration of building	Ability to provide indoor environmental condition requirements	Capital cost	Maintenance cost	Scaling character	System control requirements
Low-GWP refrigerant-based technologies						
Direct evaporative cooling (DEC) systems	None	Low	Low	High	Modular	None
Indirect evaporative cooling (IDEC) systems	None	Low	Low	High	Modular	None
Two-stage evaporative cooling	None	Medium	Medium	Medium	Modular	Medium
Desiccant-based systems	None	Medium	Medium	High	Modular	Low
Passive downdraught evaporative cooling	High	Medium	High	Low	Applicable to large volume spaces	Medium
Ground-coupled earth air tunnel systems	Medium	Medium	Medium	Low	Applicable to lower floors	Low
High-GWP refrigerant-based technologies						
Radiant ceiling system based on false ceiling	Medium	High	High	Low	Modular	High
Radiant ceiling system (structural)	None	High	High	Low	Modular	High
Chilled beams	None	High	High	Low	Modular	High

GWP: global warming potential

3.3.2 Promising technologies requiring further development (TRL ≥7)

The following technologies have been identified as promising cooling technologies that have the potential to become mainstream cooling technology, provided they undergo technological and economic optimization.

1. Radiative cooling: This technique relies on a process by which a body rejects thermal energy based on thermal radiation. It uses deep atmosphere and space as a heat sink. Radiative cooling can be achieved by applying certain kinds of coating on a body. A body with such a coating will be able to lose thermal energy deep into the atmosphere and help achieve thermal efficiency in any kind of heat exchanger. This promising technology may revolutionize the way we remove heat through cooling units.

2. Wearable cooling technology: Recent developments in the wearable and portable solutions for personal thermal comfort can help address building occupants' need for thermal comfort. Many of these technologies are based on thermoelectric cooling devices fitted in pendants or bracelets, which can be worn on body parts. Such approach relies on thermal aesthesia and certain thermal sensitive nodes of the body to provide thermal sensations. Most of these wearable devices are manually controlled, allowing the user to alter the temperature to their preferred thermal sensation levels.

3. Personal thermal comfort systems: Personal comfort systems (PCSs) target the immediate thermal ambience of individual occupants while giving them manual control over the PCS devices' operation. This allows the occupants to experience improved thermal comfort and acceptability of air movement, which, in an office setting, leads to improved productivity and general well-being. PCS operation can help create an acceptable thermal ambience even when the room air temperature is 4–5 °C higher or lower than the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) prescribed temperature limits. In addition to improving the physical and mental states of the occupants, PCS operation allows the unoccupied built volume to be kept in a relatively less-conditioned state, thereby drawing lower energy.

Global Cooling Prize

A good indication of future technology development in RAC is given by the technology choices of the eight finalists of the Global Cooling Prize. Global Cooling Prize[15] is an international initiative to promote innovative room air conditioning products. The prize has several criteria. One of these is that the cooling solution must show the potential for at least 80% lower climate impact than the baseline unit. Another is that the maximum power drawn by the solution from the electricity grid should not exceed 700 W while delivering the rated cooling capacity of 1.5 TR (5.3 kW) under standard outdoor conditions as well as over the span of lab and real-world test, which means almost 60% reduction compared to a baseline RAC.

The competition has short-listed eight concepts for testing, as listed below.

1. Advanced vapour compression technology integrated with evaporative cooling and solar PV.
2. Solid-state barocaloric cooling technology: The technology takes advantage of the properties of solid organic 'plaster crystal' materials to provide cooling.

[15]https://globalcoolingprize.org/.

3. Improved high-efficiency vapour compression system, with advanced evaporative cooling and solar PV.
4. Vapour compression technology with desiccant dehumidification.
5. Two-stage cooling system integrating a water loop and a traditional vapour compression system with a natural, low-GWP refrigerant.
6. Vapour compression technology with improved system design and a low-GWP refrigerant integrated with evaporative cooling.
7. Evaporative cooling and membrane dehumidification for independent sensible and latent cooling.
8. Evaporative cooling with membrane dehumidification using electro-osmosis principle.

It is observed that except for one, all other solutions are hybrid solutions. Figure 15 provides a summary of the key strategies employed by the eight finalists.

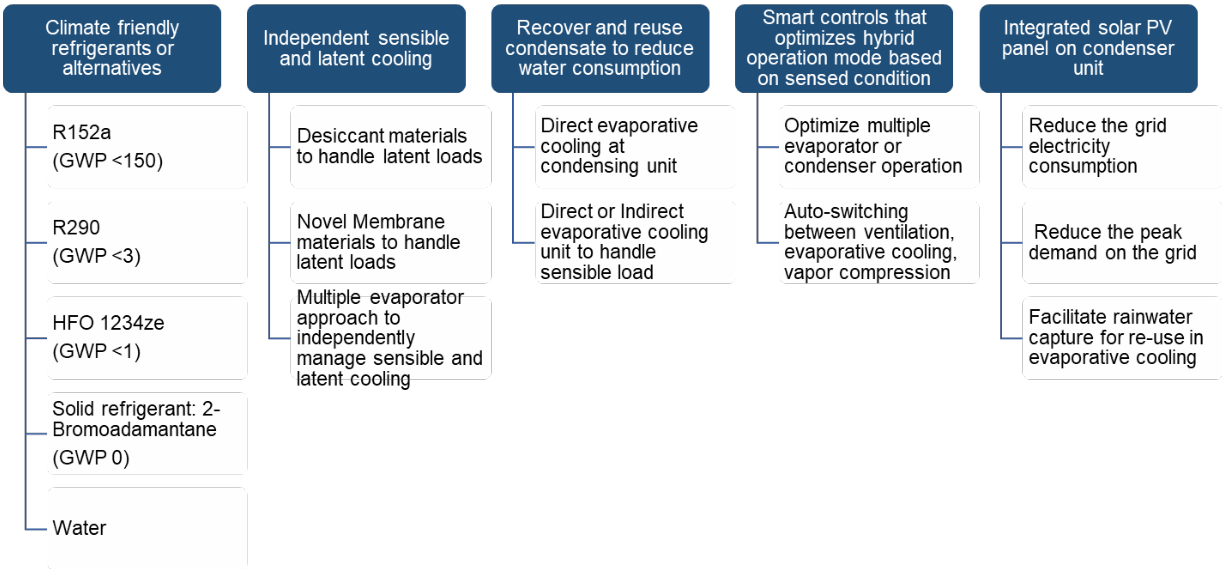


Figure 15: Summary of key strategies employed by eight finalists of the Global Cooling Prize

Based on this analysis on cooling technologies, no further recommendations are proposed in this report, as there are multiple ongoing initiatives that address similar goals. Some of the key initiatives include the Standards and Labelling Programme for RACs and fans; implementation of the recommendations of the India Cooling Action Plan, and the Global Cooling Prize (reference), which is looking to significantly change air conditioning technologies to be highly energy-efficient and reduce their dependence on refrigerants with high global warming potential. Recommendations are thus focused on building envelope parameters, which have been missed by other studies on space cooling.

4 Key Results and Assessment of Approaches

4.1 Key results

Key results from the analysis are detailed below.

4.1.1 Energy-efficient building envelope is essential for effectively reducing space cooling requirement and hence cooling electricity demand

Results show that for the year 2050 almost 900 TWh_{th}/year or 30% reduction in cooling energy requirements is possible through efficient envelope for the deep-cut scenario. This reduction can save almost 190 TWh/year of electricity in 2050.

Efficient building envelope technologies limit heat gain inside building, thus reducing overall demand for cooling and associated energy consumption. In spite of this, there has not been much focus on efficient building technologies, even though the potential benefits are largely recognized. There are multiple reasons for this:

- Only a few space-cooling studies analyse potential energy savings from building envelope, while most studies assess the impact of active cooling technologies. As a result, policy focus is on increasing the efficiency of cooling technologies rather than on efficient building envelopes to reduce the rapidly increasing cooling demand. The ICAP (MoEFCC) also focuses only on cooling technologies but does not evaluate the potential or suggest implementable measures for energy-efficient building envelopes.
- Building materials and components are grouped together with passive design measures such as orientation, and design is considered to be subjective and difficult to regulate, as opposed to active cooling technologies like fans and air conditioners. Energy-efficient building materials and components need to be recognized essentially as building envelope technologies, which will significantly reduce space cooling energy requirement. Their use and benefits are quantifiable, and not subject to a designer's use. This will help minimize the perceived implementation challenges for efficient building envelope technologies.

4.1.2 Reduction in discomfort hours due to efficient building envelope is integral for enabling thermal comfort for all

The results show that the discomfort degree hours (DDH) can be reduced by 41% in Delhi and by 56% for Mumbai if RETV is reduced from 18.5 to 8 W/m^2.

An efficient building envelope helps in extending the time period when the building is able to provide a thermally comfortable environment by reducing heat/cold ingress through the walls, windows, and roof. If the building remains unconditioned, then lower RETV helps to substantially improve (in the same order of improvement in DDH) the thermal comfort. If the building is air conditioned, then the operational time for the air conditioner is reduced and, in addition, the energy required by the air conditioner during the operational hours is also reduced, overall resulting in a substantial reduction in the energy required for cooling.

Focusing on only active cooling technologies to reduce space cooling energy use provides a solution for a limited segment of the population that can afford these technologies. ICAP assesses that 40% of the population will be able to afford cooling technologies by 2037. As a future policy outlook, it is grossly inadequate if large sections of the Indian population will not have access to basic comfort conditions in their houses. Any policy addressing space cooling should account for equity in access to thermal comfort for all and its linkage to co-benefits of health and productivity.

Additionally, similar to China, there is a possibility that adoption of air conditioners in India is faster than currently envisioned by energy models. This is evident in the LBNL study (de la Rue du Can et al., 2019), which uses China's growth metric to estimate the potential space cooling demand in India. This estimated space cooling energy requirement is significantly higher.

Reducing discomfort hours through use of efficient building materials and products needs to become a policy priority for housing projects, especially affordable housing projects, as cooling technologies are largely unaffordable for the occupants. This will also benefit the households that can afford cooling technologies by reducing the time of operation of active cooling, leading to significant energy savings. Hence, space cooling policy action needs to include comfort as an integral priority to reduce space cooling energy demand.

4.1.3 Solutions for retrofitting buildings are required to sustainably meet the 2050 cooling energy demand from the residential sector

Under the deep-cut scenario, a marginal improvement in the envelope of existing buildings through retrofit brings in significant savings. The analysis shows that for the year 2030, out of the total reduction of 189 TWh_{th}/year in space cooling requirement in the deep-cut scenario compared to the BAU scenario, almost 40 TWh_{th}/year or 21% of the reduction comes from the retrofit of existing buildings.

Building energy efficiency programmes and regulations in India have entirely focused on new buildings because of the high rates of construction. However, our analysis shows that to meet the 2050 cooling demand efficiently, existing buildings will need to be retrofitted in the near future to improve their energy performance. Buildings built since 2000 are likely to exist even in 2050.

It is essential that a suitable programme is developed for retrofitting residential buildings along with the development of cost-effective retrofitting solutions.

4.2 Approaches

As explained at the end of Chapter 3, recommendations in this study are focused on building envelope parameters, which have been missed by other studies on space cooling.

While developed countries (mainly cold countries) have seen large improvements in building envelope since the 1970s through a complementary approach based on mandatory building energy codes, voluntary or mandatory building certification, and organized market transformation programmes for building materials and components, very limited success has been achieved in improving building envelopes in developing countries (IEA and UNEP, 2018). During the last decade, several developing countries have developed building energy codes and building certification programmes, but in most cases, these are voluntary measures and the implementation remains a weak link. Some of the approaches (IEA, 2011) that can be used to improve the building envelope are discussed in the next sections.

4.2.1 Mandatory building energy codes

Building energy codes, or standards, are requirements set out by a jurisdiction (e.g., national or sub-national) that focuses on reducing the energy used for a specific end use or building component. The Bureau of Energy Efficiency (BEE) in India came up with the first building energy code in 2007, i.e., the Energy Conservation Building Code (ECBC), applicable to commercial buildings in 2007. An updated version of ECBC was released in 2017. In 2018, BEE released Eco-Niwas Samhita: Part I or the Energy Conservation Building Code for Residential Buildings (ECBC-R); part I covers only the building envelope with the main focus being to reduce the cooling and heating demand in new housing structures.

ECBC for commercial buildings has seen very slow acceptance in India since its introduction in 2007. Compared to many European countries, which started their building energy efficiency programmes with the introduction of simple prescriptive mandatory code requirements (e.g., thermal transmittance or U-value of wall, roof, etc.), India's ECBC is a complex code having many requirements. While it provides flexibility and greater choice to the building designer, it also demands a high level of technical understanding and skills.

International experience from countries like Switzerland having a federal structure like India shows that building energy codes require a long time period for compliance, implementation, and enforcement to come into place. In India, the implementation of ECBC is facing many barriers, including issues in inter-ministerial and central–state coordination, capacity concerns of the state and local governments to enforce the complex code, low level of awareness, limited availability of materials and equipment to comply with the code, and muted response from builders due to split incentives.[16]

4.2.2 Building labels or certificates

Building certification can include industry-led green building certifications (e.g., LEED, GRIHA, IGBC, etc.) as well as government/BEE-led certification programmes (e.g., star rating, building energy passport, etc.) that evaluate the performance of a building and its energy service systems. Certification may focus on rating operational energy use or the expected (or notional) energy use of the building.

Globally, the use of certification programmes is growing, with increasing acceptance of voluntary certification among high-end buildings as a means of adding value. However, there is still a lack of large-scale adoption of mandatory certification programmes outside the European Union.

In India, voluntary building certification as a market-based instrument has also not been successful in impacting large segments of the market. They have helped to a certain extent in creating awareness, but their adoption is limited to first movers in the market, as green building ratings are linked to either high-end buildings or organizational policies of corporations. The number of certified

[16] Split incentives occur when those responsible for paying energy bills (e.g., homeowner) are not the same entity as those making the capital investment decisions (e.g., builder). In these circumstances, the builder may not be inclined to make the necessary upgrades to building envelope and services when the benefits associated with the resulting energy savings accrue to the homeowner.

buildings under the BEE star rating programme is small, and most of the certified buildings are public sector/government buildings.

4.2.3 Retrofitting programmes to improve energy efficiency of existing buildings

Retrofitting programmes aim at improving energy efficiency of existing buildings. Such programmes can cover both the building envelope (insulation, windows, etc.) as well as systems (lighting, space conditioning, water heating, etc.) during renovation. Several developed countries, where most of the building stock has already been constructed, have such programmes.

Some of the key components of such programmes are as follows:

- Energy audits, energy ratings, and certification schemes
- Incentives to encourage investments in long-lasting building envelopes and system improvements
- Training and other measures to improve the quality and reliability of building retrofit services.

In India, there is some experience of pilot building retrofit programmes coordinated by BEE and EESL[17] in government buildings focussed on energy-efficient lighting and in some cases the HVAC (heating, ventilation, and air conditioning) systems. Building envelope retrofit has not been part of these pilot programmes.

4.2.4 Building products-level market transformation

Market transformation[18] programmes for building materials and products have been employed either independently or together with building codes and standards globally to ensure that materials and products are available at affordable prices for the building industry to transition to energy-efficient construction. Market transformation programmes aim at removing barriers related to low levels of consumer awareness, limited access to finance, performance uncertainties and risks, split incentives, large transaction costs, complexity in integration within existing construction practices, etc.

Market transformation has proved to be an effective programme model for a diverse range of technologies, products, and practices, which has led to large energy efficiency gains globally. A case study on improving building envelope through the Energy Star Windows programme in the Northwestern USA is presented in Box 2.

Successful examples of market-based instruments in product-level interventions in India include the following:

- Standards and Labeling (S&L) Programme for appliances: This a flagship programme of the BEE for energy rating of appliances and equipment. The programme sets minimum energy performance standards (MEPS) and provides consumers easy-to-understand information on energy consumption of appliances through Energy Star labels. The programme has been

[17] https://www.business-standard.com/article/news-cm/govt-of-india-launches-energy-efficient-buildings-programme-eesl-to-invest-rs-1-000-crore-by-2020-under-buildings-programme-117052301686_1.html.

[18] Market transformation is defined as a strategic process of intervening in a market to create lasting change in market behaviour, to accelerate the adoption of all cost-effective energy efficiency as a matter of standard practice.

successful in creating visibility of EE labels and transformed the market for energy-efficient appliances such as air conditioners, refrigerators, and televisions.

- Domestic Efficiency Lighting Programme (DELP): This has been a successful programme for EESL, where bulk procurement of LED lamps was used successfully as a market instrument to shift the market from incandescent and CFL lamps to highly energy efficient LED lamps. Bulk procurement contracts to manufacturers and an effective distribution mechanism helped in accelerating the adoption of this new technology while also reducing the costs of LED lamps significantly in the market.

However, currently, there is no such programme in India for building materials and products.

Box 2: Energy Star Windows Program in the Northwestern United States (York D. et. al., 2017)

Inefficient windows were estimated to be responsible for 25% of heating and cooling related energy costs in typical US homes in 1994, equivalent to 2% of the total US energy consumption. Accelerated adoption of available energy efficient window technologies could potentially reduce this energy use by a third (NEEA 2002). In 1997, market penetration for energy-efficient windows stood at 10-15 per cent in the North-western United States. There was low awareness about benefits of energy efficient windows, and their availability. Both production and retail costs were high. There was also a lack of educational and marketing materials. From a builder perspective, there was split incentive in investing in energy efficient windows, while the benefit will be accrued by homeowners.

In the same year, the Environment Protection Agency (EPA) and the Department of Energy (DOE) jointly launched the Energy Star Windows Program and label to provide visibility and recognition for standardized efficient windows. A year later, an alliance of electric utilities in the Northwest (henceforth 'Alliance') led a market transformation program to increase the market share for efficient windows in the residential sector. The Alliance convened various stakeholders such as regional utilities, window manufacturers, window retailers, builders, and a consortium of multiple technical agencies, labs, research agencies and trade associations etc. to develop and implement the market transformation programme.

Programme Strategy/Components

- Label and Ratings: Energy Star program technical criteria and branding of efficient windows. Uniform Rating system for efficient windows developed by National Fenestration Rating Council.
- Technical Assistance: Supported six key large manufacturers to find simple ways to refine the manufacturing processes, reduce production time and costs.
- Monetary incentives to window manufacturers to leverage Energy Star marketing and promotions as part of their product branding and information.
- Marketing strategy and aid to define clear value proposition for each stakeholder in the value chain.
  - Support to manufacturers to demonstrate how to increase market share
  - Training, marketing kits and financial aid for retailers to help them achieve higher sales margins
  - Simple messaging for consumers about the energy and non-energy benefits of Energy Star windows.
- Federal Tax incentives were in place from 2005 to 2016 to support the market.

Impact

- With an investment of $1.8 million from 1997 to 2001, the market share of Energy Star windows increased from 10%–15 % in 1997 to 66% by 2001 in the Northwest. By 2011, market share reached 95% in the Northwest and more than 80% nationally in 2014.
- By 2008, building codes in four states included the window specifications as in the market transformation effort.
- Energy Star qualifying criteria were updated and made more stringent in 2015/16 in different parts of the country.

Market actors	Role played	Policy instruments
US DOE and EPA	National-level Energy Star Windows program	Mandatory labelling program; Education and information campaigns, Tax exemptions, Monetary incentives
Northwest Energy Efficiency Alliance	Led the market transformation program effort	
Window manufacturers and retailers	Performed key implementation of program strategies	
National Fenestration Rating Council	Provided technical ratings for window efficiency to ensure uniformity	
Efficient windows consortium	Filled the education and marketing gap	

4.3 Inferences

Based on the results from this study, it is evident that energy-efficient building envelope measures are essential for meeting the 2050 space cooling demand from urban residential sector sustainably. Measures to achieve energy-efficient building envelopes, therefore, need to be included in all policies that determine construction of residential buildings in the country (e.g., PMAY), as well as space cooling-related policies and programmes (e.g., ICAP). This will also enable the vision of the space cooling policies for achieving 'thermal comfort for all', which is currently not inherent in initiatives designed around cooling technologies alone. In the short term, incorporating this in affordable housing will result in immediate benefits by reducing the discomfort hours and need for cooling. Apart from recognition of the need for energy-efficient building envelopes in policies, the assessment of available approaches can provide clues on how it can be practically implemented in India.

Energy efficiency initiatives in the buildings sector globally have mostly focused on top-down mandatory public policies such as building energy codes, mandatory targets for utilities for achieving energy savings, and mandatory building energy audits, among others, followed by market-based instruments such as incentives for code-compliant building materials and products or financing programmes for retrofitting, etc.

However, India's context is unique due to the large-scale, rapid urbanization-led construction, and a cooling-focused climate. These present a multitude of challenges with no precedence (in the largely heating-dominated climate of developed countries) in terms of policy implementation and the scale of the problem. In India, markets have been stronger in ushering innovations and system changes than top-down policies that face implementation challenges. Within market-based instruments also, building-level approaches such as certification and labeling programmes have had limited impact in India. However, product-level market transformation for energy-efficient technologies has been a more successful approach in India. Within this context, it is recommended that product-level market-based instruments are explored and employed for accelerating energy-efficient building materials and products and for reducing the 2050 residential cooling demand sustainably.

5 Recommendations

Based on the analysis in the previous chapters, we propose three key policy recommendations.

5.1 Mainstream 'thermal comfort for all' as a criterion to reduce space cooling requirement in affordable housing

Affordable housing construction in the country is determined by the National Urban and Housing Policy (2007) and PMAY (2015). The focus is largely on low-cost housing provision for economically weaker sections and lower income groups. Construction technologies are prioritized on the basis of low cost and speed of construction. Mostly, BAU construction materials have been used over the years; however, recently a few new technologies are being incorporated (e.g., monolithic concrete construction) that adversely impact the thermal comfort of the occupants of the houses due to their increased capacity to transfer heat from the external environment. There is already evidence of such housing not being popular with the occupants. Heat stress is linked to health impacts and loss of productivity in the occupants.

Additionally, if mainstreamed, these technologies will significantly increase the space cooling electricity demand in the country, as occupants will be forced to adopt active cooling technologies to maintain comfort and use them for a longer duration of time. Based on this assessment, it is recommended that construction of affordable housing mainstreams comfort requirements through efficient building envelopes that reduce the need for cooling.

Outcome: Affordable housing construction adopts comfort as an essential criterion to reduce cooling demand through efficient building envelopes

- Through an efficient building envelope (RETV 8) alone, 40%–50% reduction in cooling hours is possible.
- This will reduce the cooling demand by the same amount while ensuring thermal comfort for extended periods of time for houses without cooling technologies.

Key recommended initiatives for enabling this are detailed below:

I. **Define and include comfort criterion as a mandatory requirement for affordable housing in following policy documents:**

   a) PMAY (2015)

   b) India Cooling Action Plan (2019)

   The key stakeholders are the Ministry of Housing and Urban Affairs (MoHUA) and the Ministry of Environment, Forests and Climate Change (MoEFCC).

II. **Evidence-building through data collection and analysis:**

   a) Assess inter-linkages with health impacts and productivity

   b) Quantify building envelope performance and thermal comfort evaluation in houses constructed using traditional and new technologies to assess the impact on space cooling energy requirements

   The key stakeholders are the Indian Council for Medical Research and BEE.

5.2 Enable a market transformation programme to ensure adoption of efficient building materials and products by 2030

The recommended building envelope technologies listed in Chapter 3 have the potential for significantly improving occupant comfort and reducing cooling energy requirement, but they are not widely used. Non-technical barriers limit the incorporation of these solutions in new and existing buildings. These are largely due to market barriers – fragmentation of the supply chain of building materials comprising manufacturing, distribution, and sales network, and technical professionals and the lack of alignment with stakeholder requirements, specifically, the contractors, builders, and developers.

It is recommended to launch a market transformation programme aimed at four categories of products:

a) Bricks/blocks with low thermal conductivity (e.g., AAC blocks, hollow clay blocks)

b) High-performance windows (e.g., double-glazed windows)

c) External movable shading products (e.g., roller blinds, bamboo chicks, lamella blinds)

d) Roof tiles with low thermal conductivity and/or high solar reflectance index (SRI).

A market transformation roadmap will need to identify and address market barriers for each selected product. Table 13 provides a broad framework for identifying and addressing market barriers through suitable initiatives.

Table 13: Broad framework for identifying and addressing market barriers through suitable initiatives*

<table>
<tr><th>Identifying market barriers</th><th>Addressing market barriers</th></tr>
<tr><td>Availability: Is the technology commercially available or does it require R&D support to bring to the market?</td><td>• Product development R&D
• Field testing, performance measurement
• Demonstrations</td></tr>
<tr><td>Accessibility: Is the produce easily accessible in the market, with sufficient manufacturers to enable choice, and aligned performance standards?</td><td rowspan="2">• Simple and implementable building codes and standards
• Retrofitting programme (with defined standards)
• Incentives-led manufacturing initiative
• Strengthening supply chains</td></tr>
<tr><td>Affordability: Is the demand deterred by high upfront costs, or high installation/maintenance costs?</td></tr>
<tr><td>Awareness: Is information easily available for the market to know about the technology benefits, design, installation, and use?</td><td rowspan="2">• Standards and Labeling Programme
• Capacity building and training
• Information and awareness</td></tr>
<tr><td>Acceptance: Is the technology a good fit as a solution and is accepted by end users?</td></tr>
</table>

*Framework derived and adapted from Energy and Mines Ministers' Conference (2018)

Outcome: Construction cost from efficient building materials to be comparable to the BAU scenario by 2030 leading to wide-scale adoption

- Address the non-technical barriers for existing efficient materials and products such that these are readily available and affordable in the next 10 years
- Currently, RETV 8 envelope can be achieved at 9%–11% (INR 150 /ft^2) additional cost of construction per house.

Key recommended initiatives for addressing market barriers are detailed below.

I. **Incentive-led manufacturing initiative:** There is a need for a strategic plan to understand barriers and align financial incentives for the production of high-performance products more affordable. A large number of building components such as bricks, blocks, and windows are manufactured in the MSME sector.

   Key stakeholder: Ministry of Micro, Small and Medium Enterprises.

II. **Standards and Labelling Program:** Linking the incentive program to energy efficiency standards for these building materials and components will help in building the confidence of the industry and consumers in these products and provide visibility to energy efficient products.

   Key stakeholder: Bureau of Energy Efficiency.

III. **Retrofitting programme for existing residential buildings:** Eco-Niwas Samhita as a building code is applicable to new residential buildings. A market transformation programme should expand the scope and set standards to account for retrofitting of existing residential buildings.

   Key stakeholder: Bureau of Energy Efficiency.

5.3 Focused industry-led R&D initiative for next generation energy-efficient building envelope technologies

The selected building envelope technologies at the Technology Readiness Level (TRL) ≥7 level have potential for application and scalability in the Indian context. The potential of these technologies in terms of energy savings, applicability, costs, adaptability to the Indian context, and acceptance in the market and by stakeholders should be assessed.

To begin with, three technologies have been identified for further assessment and exploration:

a) Radiative cooling film technology to reject heat from roof
b) Aerogel-based renders, plasters, bricks, and roof tiles to reduce heat gains
c) Smart windows to reduce heat gains and improve daylighting

Outcome: Potential for new construction materials and technologies is assessed and they are adapted to India's context to enable commercialization

Key recommended initiative for enabling the programme is detailed below.

I. **Technology assessment roadmaps:** A technology assessment roadmap should comprise a systematic study to understand the future potential of the technology, and list out the support it will need for commercialization and market acceptability. Based on this technology roadmap, a focused industry-led R&D initiative should be launched.

The key stakeholder is the Department of Science and Technology.

5.4 Conclusions

This study provides a comprehensive analysis of space cooling demand in the urban residential sector in India. It takes a non-linear approach to estimate this demand by extending the scope of this demand to the entire population that will require cooling in 2050. The study does not limit the analysis to only those who can afford expensive and energy-intensive air conditioning technologies.

To address this larger demand, the study highlights the role of both building envelope as well as cooling technologies in reducing and meeting this demand effectively. This ensures that energy savings are cost-effective and the proposed recommendations are inclusive and based on equitable access to 'thermal comfort for all'.

Energy and cost-benefit analyses show that building envelope technologies provide a robust and cost-effective solution for reducing the cooling demand and extending the time period when houses can maintain comfortable temperature by 40%–50% without the use of cooling technologies. Additionally, the study recommends two broad sets of policy-related action points, taking into account the results from the study and from an understanding of India's context of past energy efficiency initiatives.

Annexure A:Modelling Approach and Methodology

A.1 **Estimation of residential built-up area (urban and rural) at the district level**

A.1.1 List of districts

- The list of districts as per the Census of India 2011 was mapped with respect to climate zone and latitude, i.e., all districts were assigned climatic zone as per the climatic zone map of India and latitude (≥23.5°N or <23.5°N).
- Newly added, name-changed, and combined/split districts of the Census of India 2001 were synced with the Census of India 2011 data. Further, all districts were subdivided into rural, urban, and total categories.

A.1.2 Estimation of population

- Population data of urban, rural, and total area of a district were extracted from the Census of India 2001 and 2011.
- The forecast of the total population of the country until 2050 was kept the same as of India Energy Security Scenario (IESS) model of NITI AYOG (Thambi et al., 2018).
- District's total population is forecasted until 2050 at a rate of country's total change in population.
- Percentage of urbanization was calculated for 2001 and 2011. Percentage of urbanization was linearly forecasted until 2050.
- Urban population of each district was calculated by multiplying the percentage of urbanization with the total population.
- Rural population of each district was calculated by subtracting the urban population from the total population.
- The year 2020 was taken as the base year for all future analysis.

A.1.3 Estimation of household size and household numbers

- Household number data of urban, rural, and total area of a district was extracted from the Census of India 2001 and 2011.
- Household sizes for 2001 and 2011 were calculated by dividing the population by the household number, specific to each district.
- Household size was linearly forecasted until 2050. However, the minimum value of 3 and maximum value of 10 was capped in the forecast (United Nations, 2017).
- Number of households after 2011 until 2050 was calculated by dividing the population by the household size.

A.1.4 Estimation of built-up area per household

- For 2011, NSSO 2006/07 data were used, which gives the built-up area per household for rural and urban areas at the state level. Data at the state level were assumed to be uniformly distributed at the district level.
- It was assumed that the household size required for a fulfilling life condition would be achieved in 2050. This is defined for urban and rural areas as per the formula below.

  For a household with two or more people, the minimum living area standard is given by:

For rural areas, the household area = 25 m^2 × no. of people + 25 m^2

For urban areas, the household area = 20 m^2 × no. of people + 15 m^2

- For the intermediate years, the built-up area per household for rural and urban areas was linearly forecasted between 2011 and 2050.
- Built-up area per household in a district's total area is calculated by the built-up area per household's weighted average for urban and rural areas. The weighted average of the number of households was considered.

A.1.5 Estimation of built-up area

- Residential built-up area for urban, rural, and total area was calculated by multiplying the built-up area per household with the number of households.
- The above data were calculated for all districts from 2001 to 2050.

A.1.6 Segregating total built-up area

- The total built-up area is segregated into existing and newly constructed areas.
- The life of a building is assumed to be 50 years; it is also assumed that the built-up area existing in 2020 will be demolished at a uniform rate every year until 2070 and will be replaced by new buildings. As per this, starting from 2020, 60% of the residential buildings will get demolished by 2050.
- All buildings demolished and reconstructed after 2020 are considered as new buildings while the remaining buildings are considered as existing buildings.
- All buildings constructed after 2020 are considered as new buildings.
- Between 2020 and 2050, there will be various construction projects that are going to be demolished and reconstructed as well as newly constructed.
- Different strategies were considered for improving the building envelope properties of existing and new buildings.

A.1.7 Estimation of number of storeys

- The average number of stories at the district level for urban areas was calculated as

$$\text{Number of stories} = \frac{\text{Total built} - \text{up area}}{\text{Total roof area}}$$

- For the urban area, a study conducted for Delhi (T. E. et al., 2013) was considered. This study gives the average number of stories as 2.5 for Delhi. This number is used for all urban areas and is kept the same until 2050.
- For rural areas, the average number of stories is considered as 1.25 for all districts and assumed to remain constant until 2050.
- For each district's total area, the average number of stories was calculated by the weighted average of urban and rural areas.

A.1.8 Estimation of residential rooftop area

- Roof area is calculated by dividing the built-up area by the average number of stories for each district for urban and rural areas for all time periods.
- The total roof area is calculated by adding roof areas of urban and rural areas.

A.2 Estimation of cooling energy requirement using ENS methodology

A.2.1 Estimation of U-value

- Wall construction data for urban and rural areas along with the respective household number for each district was taken from the Census 2011 data.
- For each construction type of wall, a U-value was calculated.
- Based on the number of households and the respective U-values, a weighted average U-value of wall was calculated for each district. The calculations are done for both urban and rural areas.
- It is assumed that the weighted average value calculated for 2011 remains the same for 2020.
- All the above steps were followed to calculate the weighted average U-value for roof as well.

A.2.2 Estimation of envelope (excluding roof) sensible heat gain

Estimation of sensible heat gains from building envelope (excluding roof) is done using the technical analysis and simulation work done for the development of ENS 2018. The steps are as follows:

- Calculation of Residential Envelope Transmittance Value (RETV) (W/m^2) for building envelope (except roof) for four climate zones, namely composite climate, hot-dry climate, warm-humid climate, and temperate climate, using the following formula:

$$\mathrm{RETV} = \frac{1}{A_{\mathrm{envelope}}}\left[\begin{array}{c} \left\{a \times \sum_{i=1}^{n}\left(A_{\mathrm{opaque}_i} \times U_{\mathrm{opaque}_i} \times \omega_i\right)\right\} \\ + \left\{b \times \sum_{i=1}^{n}\left(A_{\mathrm{non-opaque}_i} \times U_{\mathrm{non-opaque}_i} \times \omega_i\right)\right\} \\ + \left\{c \times \sum_{i=1}^{n}\left(A_{\mathrm{non-opaque}_i} \times \mathrm{SHGC}_{\mathrm{eq}_i} \times \omega_i\right)\right\} \end{array}\right]$$

where

A_{envelope} is the envelope area (excluding roof) of the dwelling units (m^2). It is the gross external wall area (includes the area of the walls and the openings such as windows and doors).

A_{opaque} is the area of different opaque building envelope components (m^2).

U_{opaque} is the thermal transmittance values of different opaque building envelope components (W/m^2.K).

$A_{\text{non-opaque}}$ is the area of different non-opaque building envelope components (m^2).

$U_{\text{non-opaque}}$ is the thermal transmittance values of different non-opaque building envelope components (W/m^2.K).

SHGC_{eq} is the equivalent solar heat gain coefficient values of different non-opaque building envelope components.

ω is the orientation factor of respective opaque and non-opaque building envelope components.

U_{wall} is the U-value of the walling material (W/m^2.K).

U_{roof} is the U-value of the roofing material (W/m^2.K).

U_{glass} is the U-value of glass material (W/m^2.K).

a, b, c are the coefficients given in Table A1.

Table A1: Values of the parameters *a*, *b*, and *c* for estimation of sensible heat gain from building envelope

Climate Zone	*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

- Calculated U-value of wall for urban and rural areas of each district was used for RETV calculation.
- For the base year 2020 calculation, a window-to-wall ratio of 15% and single clear glass (U-value: 5.8 $W/m^2.K$ and SHGC: 0.8) with 300 mm overhang is considered. This is taken as the same for all districts, and also for urban and rural areas.
- Building envelope area is assumed to be distributed equally in all directions.
- During the development of ENS 2018, a correlation between the RETV and 'sensible heat gain from building envelope (excluding roof) per unit built-up area' was developed for each climatic zone. The same correlation was used to calculate sensible heat gain from building envelope (excluding roof) per unit built-up area; multiplying it by the built-up area resulted in the total heat gains for the urban and rural areas for each district.
- The value of RETV and its penetration were varied under different scenarios (details given in section A.5) until 2050 for new and existing buildings; calculation of heat gains was done as explained above.

A.2.3 Estimation of roof sensible heat gain

- For calculation of roof gains, energy simulations were done for selected cities (Mumbai, Chennai, Kolkata, New Delhi, Ahmedabad, Nagpur, Bengaluru) in different climatic zones. The energy simulation model used for ENS 2018 development was used.
- The sensible heat gain (kWh) from roof was calculated using simulation for the following U-values: 2.8 $W/m^2.K$, 1.2 $W/m^2.K$, and 0.8 $W/m^2.K$. The roof sensible heat gain per unit area of roof is given in Table A2.

Table A2: Roof sensible heat gain per m^2 of roof

Roof U-value ($W/m^2.K$)	Roof sensible heat gain (kWh/m^2 roof area)			
	Composite	Hot-dry	Warm-humid	Temperate
2.8	129.5	129.5	149.1	111.2
1.2	64.1	64.1	74.6	56.1
0.8	44.5	44.5	51.8	39.2

- The roof U-value and its penetration were varied under different scenarios (details given in section A.5) until 2050 for new and existing buildings; calculation of heat gains was done as explained above.

- Using the average number of stories and the roof sensible heat gain/m^2 of the roof area, the roof sensible heat gain per unit of built-up area was calculated.

A.2.3 Estimation of latent load

- For the calculation of latent loads, energy simulations were done for selected cities (Mumbai, Chennai, Kolkata, New Delhi, Ahmedabad, Nagpur, Bengaluru) in different climatic zones. The energy simulation model used for ENS 2018 development was used.
- The simulation provided the latent load per unit of built-up area for each climatic zone (Table A3).

Table A3: Simulation results for latent gain per m^2 for each climate zone

Climate zone	Latent gain (kWh_{th}/m^2 built-up)
Composite	15.92
Hot-dry	15.92
Warm-humid	26.15
Temperate	11.43

- The value of latent gain was kept the same for urban and rural areas and also it was not varied with time (remained the same until 2050).

A.2.4 Estimation of total space cooling energy requirement

- Total space cooling energy requirement per unit of built-up area was calculated by adding the gains calculated as per sections A1.9–A1.11:

  Space cooling energy requirement per unit of built-up area =

  Envelope (excluding roof) sensible heat gain per unit of built-up area

  + Roof sensible heat gain per unit of built-up area

  + Latent load per unit of built-up area

- Out of the total built-up area, 70% was considered as cooled area, excluding toilets and kitchen space.
- Space cooling energy requirement for urban and rural areas of each district was calculated by multiplying the space cooling energy requirement per unit of built-up area by the respective cooled built-up area.

A.3 Estimation of cooling electricity demand and CO2 emission

A 3.1 Estimation of cooling electricity demand

- Calculation of cooling electricity demand was done by dividing the 'space cooling energy requirement' with the effective coefficient of performance ($CoP_{effective}$) of cooling appliances:

$$\text{Cooling electricity demand} = \frac{\text{Space cooling energy requirement}}{\text{CoP}_{\text{effective}}}$$

- The effective coefficient of performance ($CoP_{effective}$) of cooling appliances was assumed to be 2.75 (same as used in IESS) for the base year 2020; the target values for 2050 were set under different scenarios (details are given in Section A.5) to estimate the cooling electricity demand.

A.3.2 Estimation of CO2 emissions

- Estimation of CO_2 emissions was done by multiplying the cooling electricity demand with the emission factor (0.82 kg of CO_2/kWh) (CEA, 2018).

A.4 Estimation of connected and peak loads

- It is assumed that a 12 × 12 ft (area: 144 ft^2 or 13.4 m^2) space will have an air conditioner of cooling capacity of 1.5 ton (or 5.3 kW). This gives the cooling capacity of the cooling system as 394 W/m^2 of cooled area. Multiplying it with the cooled area will give the total cooling capacity of the cooling system.
- Connected load for the cooling system per unit cooled area is calculated by dividing the cooling capacity of cooling system per unit cooled area with the effective coefficient of performance ($CoP_{effective}$). For example, with a $CoP_{effective}$ of 2.75, the connected load for the cooling system per unit cooled area would be 394/2.75 = 143 W/m^2. Multiplying it with the cooled area will give the total connected load for the cooling system.
- Estimation of connected load for the cooling system for the year 2020 is done based on the above two points.
- Improvement in building envelope (as per the scenarios given in Section A.5) will lead to reduction in space cooling energy requirement per unit cooled area. Reduction in cooling capacity of cooling system per unit cooled area will happen in the same proportion. Again, multiplying it with the cooled area will give the total cooling capacity of the cooling system.
- Improvement in $CoP_{effective}$ (as per the scenarios given in Section A.5) will lead to reduction in connected load for the cooling system per unit cooled area. For example, if the $CoP_{effective}$ is increased to 3.0, the connected load for the cooling system per unit cooled area would be 394/3.0 = 131 W/m^2. Again, multiplying it with the cooled area will give the total connected load for the cooling system.
- For calculation of peak load or the avoided capacity addition of power plant, a diversity factor of 70% is considered (Abhyankar et al., 2017). Peak load is calculated by multiplying the connected load of the cooling system with the diversity factor.

A.5 Basis of scenarios and key parameters

To estimate the projection of envelope heat gain until 2050, we developed the BAU and deep-cut scenarios. These scenarios are assumed to be implemented in different time period, namely 2020–25, 2025–30, 2030–40, and 2040–50 (Table A4 and Table A5).

BAU is a scenario where practices such as technology execution and policy execution are assumed to be changing at a slow rate. Deep-cut scenario is where practices are assumed to be improved for better growth in an aggressive manner either through policy change or technology development/penetration. While calculating projections of sensible heat gain per built-up area through wall using BAU, RETV as 15 W/m^2 is considered for new construction at all time periods. Buildings having RETV of already less than 15 W/m^2 are excluded in the estimation and are assumed to retain the existing value. We further consider the penetration percentage of improved RETV in new constructions. The penetration percentage can be seen in Table A4.

Under deep-cut scenario, for estimating sensible heat gain per built-up area, RETV of new construction has been considered to improve from 15 to 8 W/m^2 in 30 years. Penetration of improved RETV is 100% until 2050. Existing buildings' RETV is also likely to improve to 12 W/m^2 and at a penetration of 80% by 2050.

Roof sensible heat gain per built-up area using BAU is estimated with a constant U-value of 1.2 W/m^2.K until 2050 for newly constructed building roofs and a penetration of 50%. Under the deep-cut scenario, a varying U-value is assigned to new construction roofs starting from 1.2 to 0.5 W/m^2.K with penetration up to 100% in 30 years. For existing roofs, the U-value is assumed to reach 1 W/m^2.K by 2050.

Table A4: Percentage penetration of RETV for existing and new constructions for different time periods for the different scenarios

			Time period			
			2020–25	**2025–30**	**2030–40**	**2040–50**
BAU scenario	Existing buildings	RETV	No improvement	No improvement	No improvement	No improvement
		Percentage penetration	100	100	100	100
		Roof U-value	No improvement	No improvement	No improvement	No improvement
		Percentage penetration	100	100	100	100
	New buildings	RETV	15	15	15	15
		Percentage penetration	10	25	50	50
		Roof U-value	1.2	1.2	1.2	1.2
		Percentage penetration	10	25	50	50
Deep-cut scenario	Existing buildings	RETV	15	15	12	12
		Percentage penetration	10	40	60	80
		Roof U-value	1.2	1.2	1	1
		Percentage penetration	10	40	60	80
	New buildings	RETV	15	12	8	8
		Percentage penetration	75	75	75	100
		Roof U-value	1.2	1	0.5	0.5
		Percentage penetration	75	75	75	100

In this analysis, latent gain plays a direct role in the total heat gain calculation. Using simulation, latent gain per built-up area is calculated for all climate zones. It is assumed that there is no change in latent gain values until 2050.

Under the BAU scenario, it is expected that the average effective efficiency of the cooling technology will increase at a uniform rate of 2% per annum because of the existing measures so that by 2050 the $CoP_{effective}$ will be 5.

Under the deep-cut scenario, it is assumed that the average $CoP_{effective}$ will become 7.52, which is the CoP of the most efficient RAC available in the global market (Korean cooling-season performance factor [CSPF] of 9.4, which is about 15%–20% lower when converted to Indian Seasonal Energy Efficiency Ratio (ISEER) (Abhyankar et al., 2017).

The target values for the average effective efficiency of the cooling technologies under the two scenarios are provided in Table A5.

Table A5: $CoP_{effective}$ under different scenarios and time periods

	$CoP_{effective}$				
	2020	**2025**	**2030**	**2040**	**2050**
BAU scenario	2.75	3.13	3.50	4.25	5.00
Deep-cut scenario	2.75	3.55	4.34	5.93	7.52

A.6 Impact of behavioural change

- All the above calculations were done considering a cooling setpoint of 26 °C.
- An increased cooling setpoint of 28 °C is considered to assess the impact of behavioral changes.
- Again, energy simulations were done for selected cities (Mumbai, Chennai, Kolkata, New Delhi, Ahmadabad, Nagpur, Bengaluru) in different climatic zones. The energy simulation model used for ENS 2018 development was used.
- Energy simulation provided the reduction in cooling electricity demand by changing the cooling setpoint from 26 °C to 28 °C, which was calculated for different climatic zones, as given in Table A6.

Table A6: Reduction in cooling electricity demand (ratio) for two temperature settings and climate zones

Climate zone	Ratio (cooling electricity demand with setpoint as 28 °C/cooling energy demand with setpoint as 26 °C)
Composite	0.878
Hot-dry	0.878
Warm-humid	0.882
Temperate	0.745

- Cooling electricity demand with setpoint as 28 °C was calculated by multiplying the cooling electricity demand with setpoint as 26 °C with the ratio given in Table A6.

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