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Decarbonizing India's Residential Building Sector: Insights and Pathways from a System Dynamics Model

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Highlights

- Strategic pathways for sustainable development in India's residential sector.
- Study focuses on reducing carbon impact, which is crucial for achieving the net-zero target.
- Practical implications for energy-efficient interventions, aiding informed decision-making.
- Sectoral connections and resource considerations emphasized for effective net-zero transition.
- Incorporating thermal comfort enhances the potential for significant operational energy savings.

Abstract

This study analyzed potential low-carbon pathways to achieve net-zero residential buildings in India. With the building sector contributing to 33% of global energy-related CO_2 emissions, decarbonizing it is crucial for a net-zero economy. The study used a system dynamics model—Sustainable Alternative Future for India—to capture sectoral interlinkages and explore the implications of meeting India's development goals related to energy, resources, materials, and emissions. Three scenarios were developed, constituting interventions from the building, power, and material industry sectors. The business-as-usual scenario assumes that existing policies will persist, whereas the other two decarbonization scenarios consider different levels of realistic interventions, such as electrification and behavioural shifts. The study discusses the residential cooling demand and transition cost to high-efficiency appliances. Furthermore, it highlights the importance of considering sectoral interlinkages and resource constraints in achieving net-zero energy residential buildings.

Keywords: Residential Sector, Greenhouse Gas Emissions, System Dynamics, Operational Energy, Embodied Energy

Introduction

India's building sector

India's building sector is growing rapidly, contributing to approximately 24% [1] of the nation's greenhouse gas (GHG) emissions. According to the Bureau of Energy Efficiency, the building sector is solely responsible for 30% [2] of India's energy consumption, with the residential segment accounting for 25% of total energy demands [3]. A report by the National Institute of Urban Affairs and Rocky Mountain Institute (RMI) on India's building sector—"From the Ground Up: A whole-system approach to decarbonizing India's buildings sector"—states that most of the building stock that is to exist in 2050 has not been built [4], warranting a considerable increase in emissions and energy consumption in the coming years. Since the majority of the country's building stock is yet to be built, it presents a unique opportunity for designing sustainable decarbonization pathways for the sector and to adhere to the Sustainable Development Goals (SDGs), such as SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

India is a developing country with challenges in several areas, such as housing, education, and healthcare. Amongst these, challenges related to the two core areas of housing and thermal comfort are addressed by national policies. The Pradhan Mantri Awas Yojana Scheme (PMAY) operationalizes affordable housing for all by 2024 [5]. Moreover, the Indian Cooling Action Plan (ICAP), released in March 2019 by the Ministry of Environment, Forest and Climate Change (MoEFCC), addresses thermal discomfort due to increasing heatwaves and rising temperatures and highlights the importance of access to sustainable cooling. The plan has incorporated cooling demands from different sectors and established actions to reduce cooling requirements by promoting energy efficiency and stressing passive cooling through the Energy Conservation Building Code (ECBC) [6]. Some of the targets set to be achieved by 2037–38 are to reduce cooling demand by 25–30% and cooling energy requirements by 25–40% [6].

This paper aims to present different decarbonization pathways of India's building sector to assess the impact on energy consumption, GHG emissions, and resource implications. The study draws valuable perspectives from a system dynamics model—Sustainable Alternative Futures for India (SAFARI), developed by the Centre for Study of Science, Technology and Policy (CSTEP) [7]. The SAFARI's housing sector (residential) module was used to develop three realistic scenarios, considering India's development objectives, resource constraints, and climate targets. The first scenario is a business-asusual (BAU) scenario, the second is based on moderate-level technology-based interventions on buildings and interlinked sectors, and the third includes more stringent interventions than the second one. These scenarios represent a balanced approach between India's climate targets and development goals.

Several studies have attempted to model decarbonization pathways for India's building sector, with the most significant study being based on the high-efficiency building model of the Central European University [8]. The study explored energy demand scenarios, highlighting the significance of high-efficiency buildings. The study findings indicate a possibility of halving global building thermal energy demand by 2060 through ambitious policies, while a lack of support could lead to a 34–83% increase in thermal energy demand. Furthermore, the RMI report integrates solutions and innovative financing mechanisms to transform India's building sector, addressing embodied carbon reduction, energy demand curtailment, and efficient energy utilization [4]. Unlike the previous studies, this study presents a novel perspective—introduced through the lens of a system dynamics model—and offers an alternative approach to model India's building sector.

Modeling logic

In this study, SAFARI was used to model potential decarbonisation pathways for India's building sector till 2100. The model focuses on the demands arising from achieving India's development goals pertaining to different economic sectors. Socio-economic parameters, such as population and gross domestic product (GDP), are also considered. The GDP output is obtained from a macroeconomic computable general equilibrium model that is soft-linked to SAFARI, thereby ensuring macroeconomic consistency. The model works in a bottom-up manner to provide a more comprehensive and nuanced understanding of the interdependencies between sectors and the trade-offs that must be made to balance development objectives with climate action [7].

By using the modeling software Stella Architect, SAFARI estimates sectoral demand in a dynamic and non-linear manner, capturing the synergies and feedback loops that exist between different variables over time. The model explores the implications of meeting development goals on materials, energy, resources, and emissions.

The residential building sector in SAFARI has a housing shortage, new construction, material, appliances, and cooking modules causally connected with each other, along with interlinkages in industry, power, land, and the transport sector, as depicted in the causal loop diagram in Figure 1.

Framework and Assumptions

Housing module

The "Housing for All" development goal was set to meet the housing shortage by 2024 through PMAY Urban and Rural (PMAY-U and PMAY-R). Under PMAY-R and PMAY-U, 2.95 crore [5] and 1.20 crore [9] houses have been sanctioned respectively.

Shortage calculation

The housing module examines the dynamic housing shortage in India, taking into account a timeline till 2100 with the base year as 2011. The housing type for urban areas is divided on the basis of the income group—Economically Weaker Section (EWS), Low Income Group (LIG), Middle Income Group (MIG), and High-Income Group (HIG). The existing housing stock for both urban and rural is classified into various age groups: less than 1, 1–5, 5–10, 10–20, 20–40, 40–50, 50–60, 60–80, and more than 80 years. Furthermore, the structural condition of the existing houses within each age group is considered as good, satisfactory, and bad [10], [11]. For the new stock projected by the model, the age groups are 0–30 and 30–50 years, which are structurally considered as good.

The following are the factors considered for calculating the housing shortage:

1. ***Obsolescence/Dilapidation***: As houses pass through age cycles, they become dilapidated and contribute to a housing shortage. In this model, the shortage caused by aging housing stock consists of the following houses:
    - All those houses that are more than 80 years old and houses between 40 to 80 years old that are structurally in bad condition from the housing stock of 2011 are considered as obsolete.
    - Newly constructed houses will become part of the aging housing stock once they reach the age of 50 years.
2. ***Congestion factor*** indicates the percentage of households with no separate rooms for couples. According to the 2011 population census data, the estimated congestion factor is 18.42% in urban (EWS/LIG) and 6.5% in rural areas [11].
3. ***Homelessness*** is estimated to be around 0.53 million in urban and 0 in rural areas [11].
4. ***Others***:

Percentage of housing stock reconstructed annually due to natural disasters. Voluntary reconstruction by MIG/HIG households.

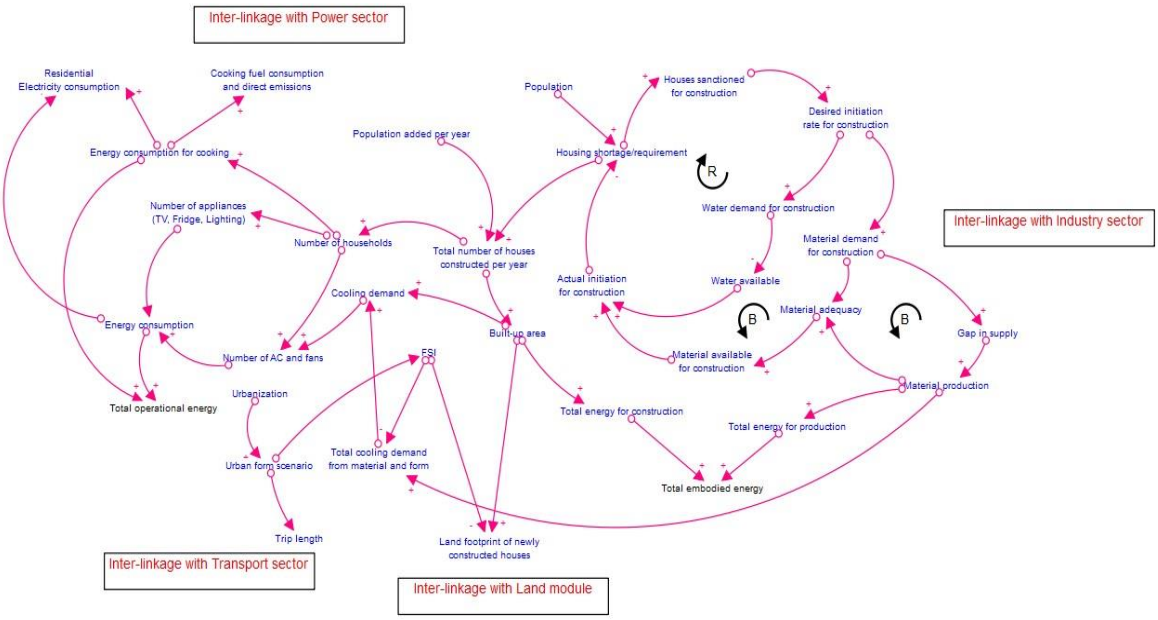

Figure 1: Causal loop diagram for the residential building sector

Shortage filling

The sanction rate to meet the housing shortage is a user input function that acts as a policy lever. The sanction rates are based on four different scenarios, namely, rent sanction rate based on the PMAY scheme, user input sanction rate, and SDG 2030 sanction rate.

Built-up area

The total built-up area is calculated on the basis of the existing housing stock, the total houses added from shortage filling and multiplied by the average built-up area for each housing category. The built-up area considered for each housing type is listed in Table 1.

Table 1: Built-up area assumption

Housing category	Built-up area per house (m^2)		Remarks
	2011	2100	
Urban (EWS–LIG) [12]	30	100	Linearly interpolated for intermediate years
Urban (MIG–HIG) [13]	100	180	
Rural	60 across all years		

Materials

Demand calculation

The SAFARI model takes into consideration the demands for cement, steel, sand, aggregate, and water. In addition to accounting for conventional materials, such as burnt clay bricks (BCBs) and solid cement concrete (CC) blocks, SAFARI accounts for alternative construction materials, such as hollow CC blocks, fly ash blocks, fly ash–lime–gypsum blocks (FaLG), autoclaved aerated concrete blocks (AAC), and stabilized earth blocks (SEBs). The user interface of SAFARI allows one to select from two alternative material scenarios with a predefined proportion of these materials. Users can also try different combinations by changing the proportion of these materials to obtain the desired outcome [14].

Embodied energy estimation

The total required quantity of each material (M_i) is computed as a product of material requirement per square meter floor area (M_a), residential floor area (A), and percentage of floor area under that material (P_i).

$$M_i = M_a \times (P_i \times A) \quad (1)$$

The total embodied energy of all materials is calculated using the following equation:

$$E = \sum_i^n (M_i \times e_i) \quad (2)$$

Where e_i is the embodied energy of each material type per unit.

Cooking

The calculation for cooking energy is based on different types of fuels and their subsequent emissions in all urban and rural households. The following formula is used:

$$\boldsymbol{Number\ of\ households\ (HH)\ using\ a\ fuel\ type} \times ((\boldsymbol{Average\ useful\ cooking\ energy\ required\ per\ HH})/(\boldsymbol{Cooking\ efficiency\ of\ that\ fuel})) \tag{3}$$

The five types of fuels considered in this model are liquid petroleum gas (LPG), electric, pressurized natural gas, biomass, and others (inclusive of coal, kerosene, and biogas).

1. Number of households using a fuel type is calculated by multiplying the cooking percentage share of a fuel type and the total number of households. Historical percentage share of fuel type data is sourced from India Energy Security Scenarios (IESS) [15] and Council on Environment, Energy and Water (CEEW) [16] and calibrated accordingly.
2. Cooking efficiency data for different fuels are adopted from IESS [15].
3. Useful cooking energy is assumed as 7.09722e-7 TWh, as per a CEEW report [17].
4. Emissions from fuel are calculated using the following formula:

$$\boldsymbol{Fuel - wise\ cooking\ energy} \times \boldsymbol{Emission\ factor\ of\ that\ fuel} \tag{4}$$

Appliances

The energy consumption of each appliance is calculated separately for urban and rural households by using the following formula [15]:

$$Total\ number\ of\ appliances \times Hours\ of\ use \times Power\ consumption \times Efficiency\ of\ appliance \tag{5}$$

The appliances considered in the model are TV, fridge, fan, air conditioners, and lighting.

1. Number of appliances is obtained by multiplying the number of households and appliance penetration for urban and rural households, wherein the penetration values are adopted from IESS [15].
2. Hours of use of a particular appliance.
3. Power rating is classified as low, medium, or high on the basis of the energy efficiency of the appliance, which is sourced from IESS [15].
4. Efficiency of appliance has four different scenarios of efficiency shares—A, B, C, and D, with each having a different percentage mix of low, medium, and high efficiency. Of these, A is the lowest efficiency scenario with a maximum number of low-efficiency appliances, whereas D is the most desirable scenario with a maximum number of high-efficiency appliances. The four efficiency trajectories are shown in Table 2.

Table 2: Efficiency trajectories

	Efficiency A			**Efficiency B**			**Efficiency C**			**Efficiency D**		
Year	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
2011	0.98	0.01	0.1	0.98	0.01	0.1	0.9	0.01	0.1	0.98	0.01	0.1
2022	0.79	0.105	0.105	0.79	0.105	0.105	0.79	0.105	0.105	0.79	0.105	0.105
2047	0.79	0.105	0.105	0.45	0.275	0.275	0.35	0.3	0.35	0.03	0.05	0.92
2070	0.79	0.105	0.105	0.45	0.275	0.275	0.2	0.4	0.4	0.02	0.03	0.95

Cost of transition to high-efficiency appliances

The cost of transition to high-efficiency appliances is inclusive of CAPEX and OPEX. The model has four different efficiency trajectories: A, B, C, and D. These signify different percentage shares of low-, medium-, and high-efficiency appliances, wherein trajectory A has a large number of low-efficiency appliances and D has a maximum of high-efficiency appliances. The cost is calculated for all four efficiency trajectories of different appliances considering their entire lifecycles. CAPEX costs are estimated using the cost of appliances sourced from IESS. The calculation for OPEX costs is based on average electricity tariff rates for tier 1 cities, tier 2 cities, and rural towns, as sourced from tariff booklets. The difference between the total cost for low-efficiency and high-efficiency trajectories discounted over the modeling timeline gives cost savings.

Cooling demand

Cooling demand is calculated for both urban and rural households by adding cooling demand due to sensible and latent heat. The sensible heat gain is the result of the changing inside and outside temperatures and occurs through building envelopes and roofs, whereas the latent heat gain occurs due to humidity present in the air. The acceptance level of both these heat gains is responsible for maintaining a thermally comfortable environment. The total cooling load is calculated by assuming the setback temperature as 26°.

Sensible heat gain: Cooling demand from building envelopes

This is calculated using the Residential Envelope Heat Transmittance (RETV) formula adopted from Eco-Niwas Samhita (ENS) 2018 [18].

$$RETV = \frac{1}{A_{envelope}} \times \left[\{a \times\times \sum_{i=1}^{n}(A_{oppaque_i} \times U_{non-oppaque_i} \times \omega_i)\} + \{b \times \sum_{i=1}^{n}(A_{oppaque_i} \times U_{non-oppaque_i} \times \omega_i)\} + \{c \times \sum_{i=1}^{n}(A_{oppaque_i} \times SHGC_{eqi} \times \omega_i)\}\right] \quad (6)$$

The variables in the RETV formula carry the same meaning as defined in the ENS code. Four climatic zones—warm and humid, hot and dry, composite, and temperate—are considered, and the RETV calculation is performed by equally dividing the housing land area under the warm and humid zone (50%) and the combined zone of hot and dry and composite zones (50%). As India has a small proportion of temperate area, it is considered negligible in the calculation. Similarly, weighted averages are taken for orientation and latitude factors to provide a nationally relevant estimate. Subsequently, RETV is converted to a cooling load by using linear regression from the energy simulation model [19].

Sensible heat gain: Cooling demand from roofs

Cooling demand from roofs is calculated through linear regression of thermal transmittance due to roofs. Thermal transmittance of a roof is calculated using the following formula sourced from ENS 2018:

$$U_{roof} = \frac{1}{A_{roof}} \left[\sum_{i=1}^{n}(U \times A)\right] \quad (7)$$

The variables carry the same meaning as described in the ENS code. Considering the scale of the study, an aggregate U value based on different materials from all states is derived for rural and urban data sourced from CENSUS 2011 [20]. The average height considered to obtain roof area is 1.25 floors for rural areas [21]. The number of floors for urban areas is dependent on Floor Space Index (FSI) scenarios, which are further segregated into HIG/ MIG and EWS/LIG.

Latent gain

Energy simulations were performed to calculate latent loads for different climatic zones by using the energy simulation model [21]. The latent load per unit built-up area obtained from these simulations was kept the same for urban and rural areas and constant for the modeling time horizon.

Cooling demand estimation

The total space cooling requirement is calculated by adding sensible heat gain and latent heat gain, multiplied by 70% of the total built-up area, to exclude kitchen and washroom spaces. The cooling requirement is converted into cooling electricity demand by using the following equation:

$$Cooling\ electricity\ demand\ (KWh) = (Space\ cooling\ Requirement\ (KWh)) / COPe \quad (8)$$

The equivalent coefficient of performance (COPe) gives the efficiency of the cooling technology used. It is considered as 2.75, with an increase of 2% per annum reaching a maximum of 5 [21].

Interlinkages with Other Sectors

Transport sector

The interlinkage between the transport and building sectors is defined through urban forms, where FSI plays an important role. For urban sprawls, the FSI considered in the model is 0.75, which extends the city boundary limit and increases the trip length, thereby impacting transport sector emissions. For a compact city scenario with an FSI of 8, the city infrastructure tends to densify. This results in shorter trip lengths, leading to fuel and energy savings.

Industry sector

The housing module interacts with the cement and steel segments of the industry module through its resource demand, influencing resource availability. The industry module assesses the available resources and determines the actual construction rate achievable based on this availability. If there is excess demand that surpasses the current production capacity, the industry module incrementally increases cement and steel production to meet the demand.

Land

The total built-up area in the housing module depends on two factors—the number of houses owned per household and the average size of each house (Table 1). The total land needed for residential construction includes the built-up area per unit and effective common space. The net new land required is determined by subtracting the land recycled from dilapidated housing (calculated using SAFARI) from the total land required for construction.

Power sector

Power sector linkages with the housing module are through electricity demand and consumption. Lower emission factor from grid supply tends to reduce operational emissions from the sector. Moreover, higher penetration of renewable sources and nuclear power in the energy mix will generate clean power sources to fuel housing appliances, resulting in reduced emissions.

Scenario Development

The BAU scenario incorporates India's current policies and guidelines, such as PMAY, ICAP, ENS, Minimum Energy Performance Standard, and National Energy Policy. Table 3 lists the combination of policy interventions used to build two decarbonization scenarios DS-A and DS-B, wherein DS-A is a more pessimistic scenario than DS-B. Furthermore, these scenarios are a mix of technological interventions, electrification, and behavioural-based shifts.

Table 3: Scenario assumptions

Sector	Intervention	DS-A	DS-B
Buildings	Electric cooking penetration	50% LPG and 50% electric in urban households; 60% LPG and 40% electric in rural households by 2070	100% electric in urban and rural households by 2070
	Appliance efficiency	Switching from Efficiency B to C	Switching from Efficiency B to D
	Alternative construction material usage	Predominantly AAC and Fly-ash blocks	Predominantly AAC, Fly ash, and SEB blocks
	Urban form	Sprawls with 0.75 FSI	Compact cities with 8 FSI
Interventions in other sectors having interlinkages with the building sector			
Industry	Electricity met by low-carbon grid for the production processes of cement and steel by 2070	100%	100%
Cement	Type of cement production	40% Portland Pozzolana + 40% Portland Slag + 20% Ordinary Portland by 2070	100% Portland Pozzolana
	Fuel share in the cement production process	$1/3^{rd}$ Hydrogen +$1/3^{rd}$ alternative fuel + $1/3^{rd}$ electric by 2070	50% Hydrogen + 50% electric by 2070
	Cement efficiency target year	2050	2050
	% Electricity intensity reduction due to efficiency	50% by 2050	50% by 2050
Steel	Fuel share in the steel production process	BF-BOF(blast furnace): 40%, hydrogen: 20%, and scrap steel: 40% by 2070	Hydrogen: 50% and scrap steel: 50% by 2070
Power	No new coal power plant to be sanctioned after	2025	2025
	Nuclear power capacity by 2070	15.5 GW	292 GW (high uptake due to policy targets)
Land	Land recovered from the demolition of dilapidated houses	Reclaimed for constructing new houses	

Results and Findings

The annual energy consumption and GHG emissions for the three scenarios are presented in Figures 2 and 3, respectively. Moreover, the space cooling requirement for both urban and rural residential sectors is shown in Figure 4.

BAU scenario: This scenario accounts for policy interventions focused on the development goals of the country and a decent quality of life. In this scenario, high embodied emissions were observed in the building sector because of the high percentage share of conventional materials, such as BCBs. Operational energy includes energy consumed by appliances and cooking within households. Most appliances in this scenario are low efficient, leading to increased energy consumption. In urban and rural households, LPG is the primary cooking fuel used, and the penetration of electric fuel remains low. Moreover, rural households have a large share of biomass fuels. In the power sector, electricity supply is driven by coal. Similarly, production processes for cement and steel plants are driven by coal and blast furnaces, respectively, thereby increasing embodied emissions of the building sector.

DS-A: In this scenario, a reduction in energy consumption by 12% (2.16 EJ) was observed compared with the BAU scenario by 2070. The operational energy was 12% (1.9 EJ) less, and embodied energy was 15% (0.26 EJ) lower than those in the BAU scenario. A reduction in emissions by 16% (0.26 $GtCO_2e$) was observed compared with the BAU scenario by 2070, wherein operational and embodied emissions account for 14% (0.21 $GtCO_2e$) and 34% (0.05 $GtCO_2e$) reductions, respectively. This can be attributed to the moderate electrification level in cooking and industry production processes. Embodied emission reduction is primarily due to the replacement of BCBs with alternative construction materials, such as AAC and Fly ash bricks. Most appliances considered in this scenario have medium efficiency.

DS-B: A reduction of 41% (7.37 EJ) in energy consumption was observed in this scenario compared with the BAU scenario by 2070. Wherein, the reduction in operational energy is 42% (6.74 EJ), and that in embodied energy is 37% (0.63 EJ) compared with the BAU scenario. A total emission reduction of 51% (0.82 $GtCO_2e$) was observed compared with the BAU scenario by 2070. Operational and embodied emission reduction account for 49% (0.72 $GtCO_2e$) and 74% (0.11 $GtCO_2e$), respectively. Operational energy and emissions decrease significantly due to high electrification in cooking and an increased share of highly efficient appliances. Industry production processes are also highly electrified in addition to the high usage of hydrogen fuel and the high percentage of recycling for steel plants, which drive down the embodied energy of cement and steel. Furthermore, the material composition in this scenario comprises of AAC, Fly ash, and SEB bricks.

Net-zero potential: The realistic interventions for both decarbonization scenarios, while similar, are implemented in higher capacities for DS-B than for DS-A. While these interventions can cut back energy consumption and emissions to a certain extent, reaching net zero will involve high dependency on aggressive scenarios for buildings and interlinked sectors. Operational emissions are contributed by the electricity consumption in buildings. Therefore, a push for policy and the implementation of supplyside interventions in the power sector, such as solar rooftop solutions, increased renewable mix in the grid supply, battery storage, and carbon capture, utilization, and storage, will nullify operational emissions from the building sector. Assuming a zero-emission grid by 2070 would reduce the overall emissions by 75%. Embodied emissions of the main building materials can be reduced by incorporating a high percentage share of green-hydrogen-based cement and steel plants. Extensive electrification of the industry has also been a widely discussed lever for decarbonization, which in turn is dependent on the extent of the greening of the grid. Apart from these, more technology advancements to replace energy-intensive materials would reduce embodied emissions, paving the way for a net-zero residential building sector.

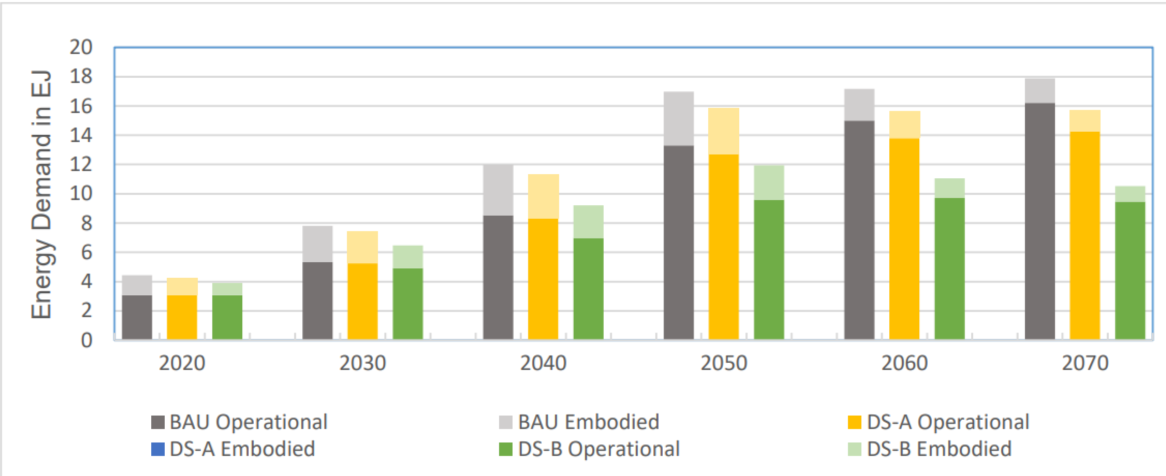

Figure 2: Energy demand from the residential building sector

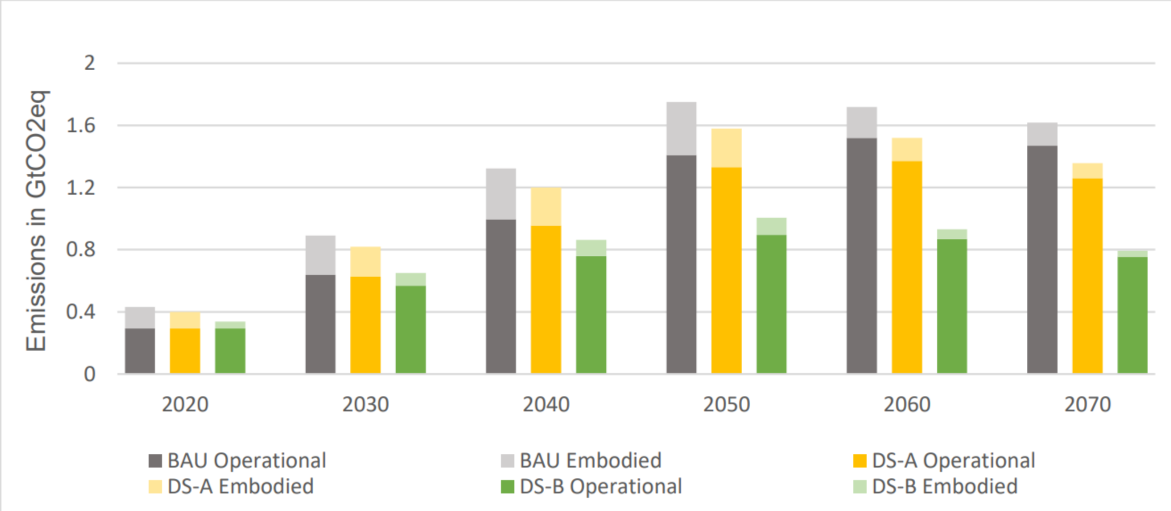

Figure 3: GHG emissions from the residential building sector

Cooling Demand Projections - BAU

The total space cooling requirement for thermally comfortable homes across India was 2388 TWh in 2020, which may reach 4411 TWh in 2070 (Figure 4). The corresponding electricity demand for cooling will increase from 878 TWh in 2020 to approximately 882 TWh in 2070, owing to a 2% per annum increase in COPe value from 2.75 for the base year. The space cooling requirement for urban households will increase from 758 TWh in 2020 to 3630 TWh in 2070, whereas for rural households, it will decrease from 1630 TWh in 2020 to 781 TWh in 2070. This is attributable to the decadal decrease in rural built-up areas and increases in urban built-up areas, owing to the swift urbanization. By considering higher COPe for the base year, this electricity demand would be further reduced. This indicates that switching to high-efficiency appliances will lower the electricity consumption for maintaining a thermally comfortable environment. In 2020, driven by the average number of cooling appliances per household, the annual electricity consumption for cooling was 207 TWh—47% of the total electricity consumption for the residential sector. This means that only 24% of the 'thermal comfort' requirements were met for the aggregate population. However, with rising incomes and urbanization, appliance ownership trends are projected to increase exponentially, which will drive the residential sector's electricity demand in the future. As per our projections based on appliance ownership trends, the electricity demand from cooling appliances will overshoot 'thermal comfort' requirements by 2035 and continue to burgeon to 2.5 times the requirement by 2050. This indicates a huge opportunity for energy savings in the sector, arguably with a shift in regulation to incorporate the 'thermal comfort' aspects. In terms of avoided emissions, it will amount to 640 million tCO_2e in 2050.

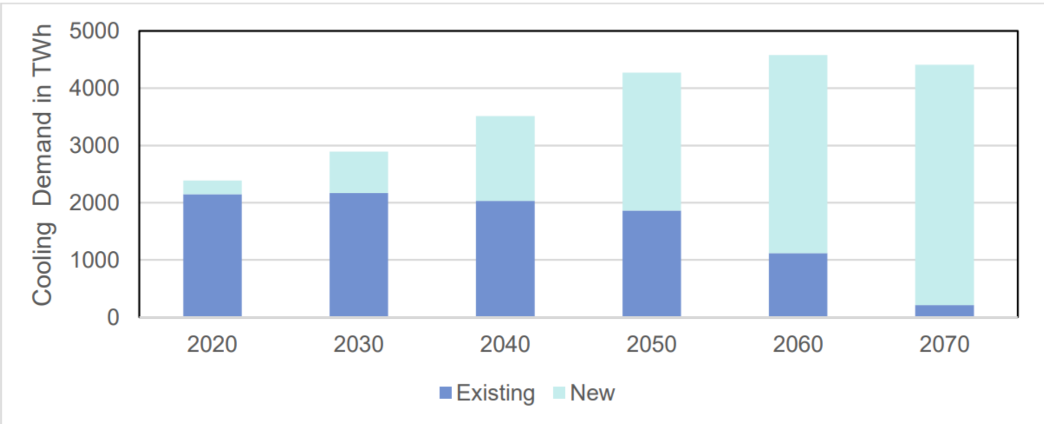

Figure 4: Cooling space requirement for the residential building sector

Cost of transition to high-efficiency appliances

Although high-efficiency appliances have a high purchase cost, they would lower the electricity consumption and maintenance cost, thereby reducing the operating cost. Switching to high-efficiency appliances would result in cost savings in the long run. The SAFARI cost module assesses the cost of transition to highly efficient appliances. Factoring the discount rate, the cumulative cost saving from the transition would be approximately INR 51.68 trillion by 2070. The CAPEX of appliances will reduce over time as the technology matures, resulting in increased cost savings.

Conclusion

In this study, SAFARI was used as a modeling tool because it is based on a system thinking approach, which allows for capturing interlinkages and complexities of dynamic systems. As per the Intergovernmental Panel on Climate Change classification, the building sector is considered as a small category under 'other fuel combustion', which in the Indian context, contributes to less than 8% of emissions directly. The 'emissions value chain' of the building sector was mapped using SAFARI, with the results indicating that buildings are responsible for 11–13% of the country's GHG emissions. The study, therefore, highlights the need for cross-sectoral collaboration to achieve net-zero emissions. Deep decarbonization of the building sector is impossible without aggressive mitigation action in the construction sector, as well as in the manufacturing industries. Policy instruments, such as carbon pricing, can perhaps drive the market toward alternative low-carbon materials and green cement and steel, as mentioned in the previous sections.

Cooling demand has emerged as an important driver to reduce operational emissions because it is expected to increase substantially in the future with rising population, incomes, and lifestyle changes. While only 40% of the 'thermal comfort' demand is being met currently, cooling appliance ownership trends point to a scenario of probable overconsumption and, thus, increased emissions in the future. A policy-based regulation tied with the building codes—with a lens of 'thermal comfort for all' as a development goal to be achieved equitably—can potentially help reduce electricity consumption from the residential sector and, consequently, the emission load on the power sector.

This study only explored cooling demand from building typology and climatic zones and did not consider the effect of urban heat islands (UHIs may be significant in the coming decades) on cooling demand. Urban densification, when coupled with increasing temperatures, will lead to a pronounced UHI effect in cities, thereby causing thermal discomfort. This will, in turn, drive up the use of air conditioners, leading to more GHG emissions and ultimately creating a ripple effect on urban heat. The DS-A and DS-B scenarios are also in line with policy developments that are expected to happen in the coming years. However, the target of net-zero buildings can only be achieved by shifting to more aggressive interventions in the power and industry sectors, which will directly drive down the building sector emissions.

The study accounts for the residential building segment, which has a major contribution to the building sector. However, the commercial building segment also accounts for approximately 9% of India's total electricity demands [22]. Thus, this also needs to be modeled to understand holistically and aim for net-zero pathways for the building sector.

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