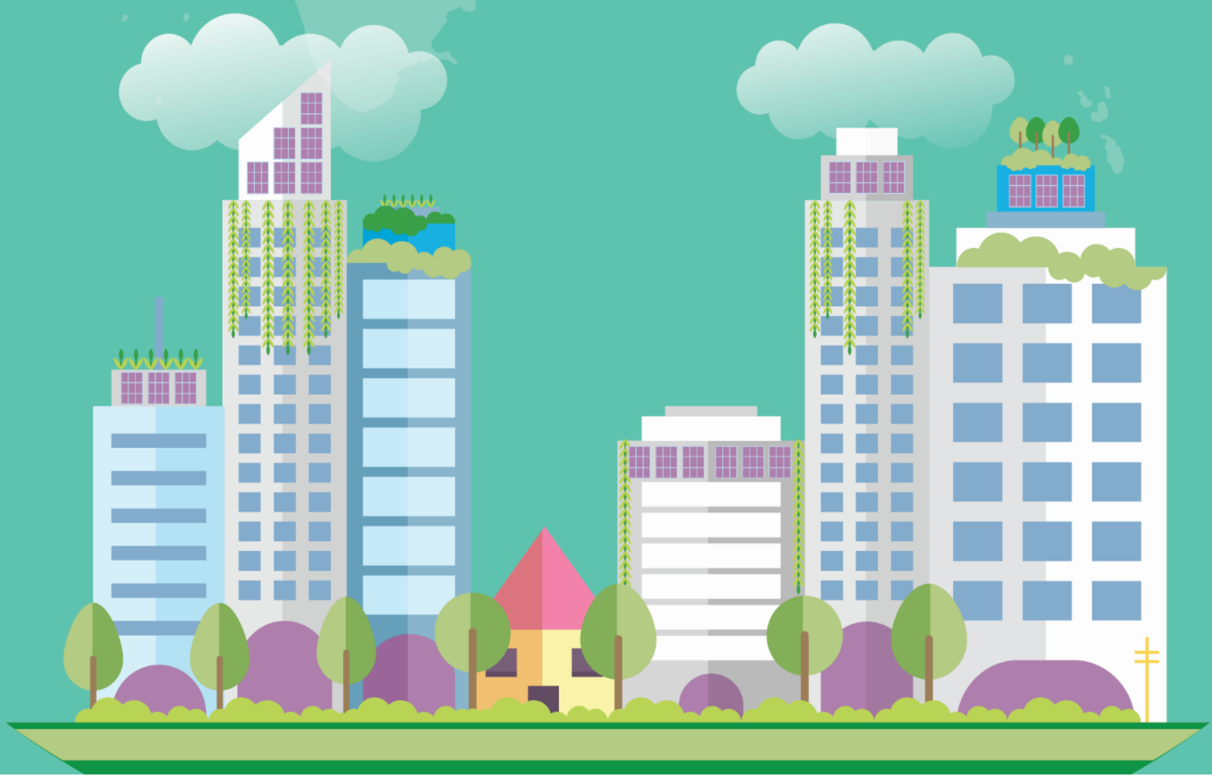
CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Pathways to Steer India's Buildings Sector Towards a Net Zero Future



Pathways to Steer India's Buildings Sector Towards a Net-Zero Future

Center for Study of Science, Technology and Policy

March 2024

Edited and Designed by CSTEP

Disclaimer

Contributors: Divya Davis, Kunal Jagdale, Kaveri Ashok, Ramya Natarajan, Sarah Khan, Sweta Bhushan, and Upasna Ranjan

(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)

This report should be cited as: CSTEP. (2024). Pathways to steer India's buildings sector towards a net-zero future. (CSTEP-RR-2024-02)

March 2024

Center for Study of Science, Technology and Policy

Bengaluru

18, 10th Cross, Mayura Street
Papanna Layout, Nagashettyhalli
RMV II Stage, Bengaluru 560094
Karnataka (India)

Noida

1st Floor, Tower-A
Smartworks Corporate Park
Sector 125, Noida 201303
Uttar Pradesh (India)

Tel.: +91 (80) 6690 2500
Email: cpe@cstep.in

Acknowledgements

We extend our gratitude to Shakti Sustainable Energy Foundation for the support that made this project possible.

We also would like to express our sincere appreciation to the esteemed experts who enriched this study with their knowledge and insights. Prof. Jyotirmay Mathur, Professor-HAG, Malaviya National Institute of Technology, Jaipur, Ms Shatakshi Suman, Deputy General Manager, Lodha Group, Mr Anurag Tamhankar, Director, Biome Solutions, Ms Smita Chandiwala, Principal, Energe-se, Mr Prabhakaran Palanisamy, Research Scholar, Anna University, and Mr Yasin Khan, Counsellor, Confederation of Indian Industry, have played pivotal roles in sharpening our understanding and shaping the recommendations.

Special thanks are due to Dr Sameer Maithel, Independent Clean Energy & Sustainability Practitioner, Dr Saket Sarraf, Principal, PS Collective, Prof. Gayathri Aaditya, Head of Planning Department, NITTE School of Architecture Planning and Design, Ms Amanda Thounaojam, Senior Associate, Indian Institute for Human Settlements, Mr Arpan Golechha, Senior Project Associate and Mr Anuj Talwar, Researcher, World Resources Institute, Mr Vaibhav Gupta, Associate Director, KPMG, Mr Kaustubh Phadke, General Manager, Global Cement and Concrete Association, Mr Narendra Pai, Senior Research Associate and Mr Atul Kharabe, Researcher, Prayas, and Ms Sakshi Nathani, Assistant Program Manager, Shakti Sustainable Energy Foundation, for their valuable feedback and suggestions that have significantly strengthened our model.

Further, our gratitude extends to Dr S S Krishnan, Advisor, CSTEP and Dr Indu Murthy, Climate, Environment and Sustainability Sector Head, CSTEP whose timely reviews, feedback, and encouragement have been indispensable in refining our research.

Finally, we thank our Communications and Policy Engagement team, particularly Ms Garima Singh, Senior Editor, and Ms Bhawna Welturkar, Communication Design Manager, for the editorial and graphic design contributions, which have enhanced the overall quality and presentation of this report.

Executive Summary

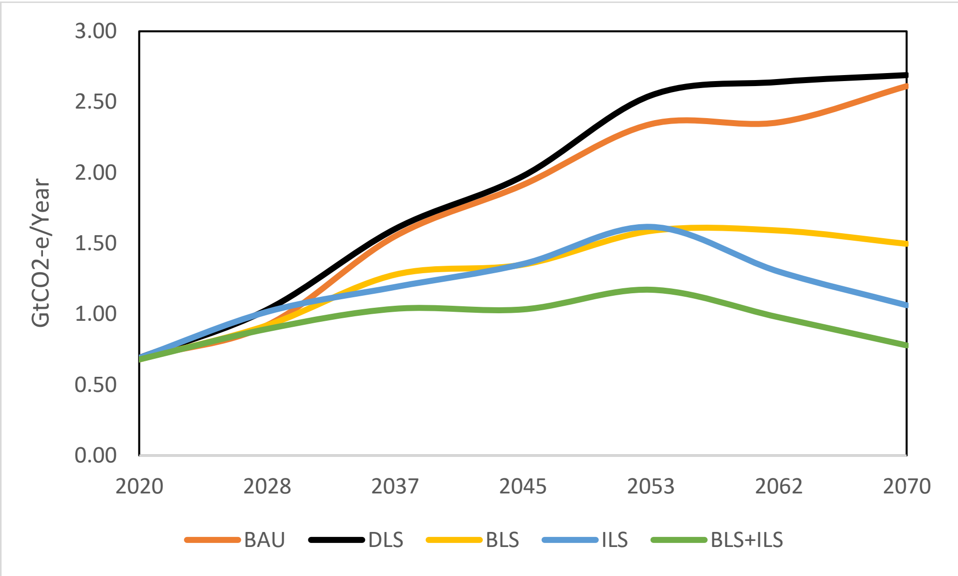
In the face of the global imperative to limit the rise in temperatures to 1.5 °C (above pre-industrial level), as outlined in the Paris Agreement, nations have been striving to transition towards a net-zero economy. This challenge is particularly pronounced for India, where the dual goals of fulfilling developmental aspirations and curbing greenhouse gas (GHG) emissions pose a complex challenge. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) assessed the remaining global carbon budget (from 2020 onwards)—for a 50% chance of limiting global warming to 1.5 °C—to be 500 $GtCO_{2\text{-}e}$. India's fair share of this global budget is estimated to be around 89 $GtCO_{2\text{-}e}$ by the Climate Equity Monitor. India's buildings sector significantly contributes to energy demand and GHG emissions. This is expected to rise further as most of the buildings that will exist in India in the next 30 years are yet to be built. Addressing the challenges in this sector, therefore, assumes immense significance not only for progressing towards the nation's developmental goals but also for steering it on a more sustainable trajectory. As such, this report explores different decarbonisation pathways for India's buildings sector, examining the complexities and opportunities inherent in achieving this transformative objective.

Objectives and Approach

The objective of the study was to develop net-zero pathways for India's buildings sector by 2070, using the system dynamics model—Sustainable Alternatives Futures for India (SAFARI) —developed at the Center for Study of Science, Technology and Policy (CSTEP). The model primarily focusses on accommodating the demands stemming from India's development goals, which impact energy requirements and emissions across various economic sectors. Taking a bottom-up approach, the model provides a comprehensive understanding of the interdependencies between sectors. The modelling framework highlights the trade-offs essential for balancing development objectives with climate action imperatives, offering a strategic framework for navigating India's sustainable development journey, in the context of the buildings sector up to 2070. For this, the study explores five different scenarios:

- **Business-as-usual scenario (BAU)** evaluates the impact of maintaining current policies and trends without additional climate-based targets.
- **Decent-living-standards scenario (DLS)** explores the impact of meeting developmental goals such as housing, education, healthcare, and thermal comfort for all, on energy consumption.
- **Buildings-led scenario (BLS)** assesses decarbonisation interventions related to the buildings sector, encompassing initiatives in the areas of cooking fuels and household appliances, along with those centred on passive design and green buildings principles.
- **Industry-led scenario (ILS)** evaluates the impact of decarbonisation interventions in allied industries such as cement, steel, aluminum, and power.
- **Buildings & industry-led scenario (BLS+ILS)** integrates all interventions applied in the above two scenarios (BLS and ILS) and assesses the overall mitigation potential of the buildings sector.

The annual GHG emissions of the buildings sector[1] across all the scenarios considered are presented below:



Annual GHG emissions (operational + embodied) from the buildings sector

Key Observations:

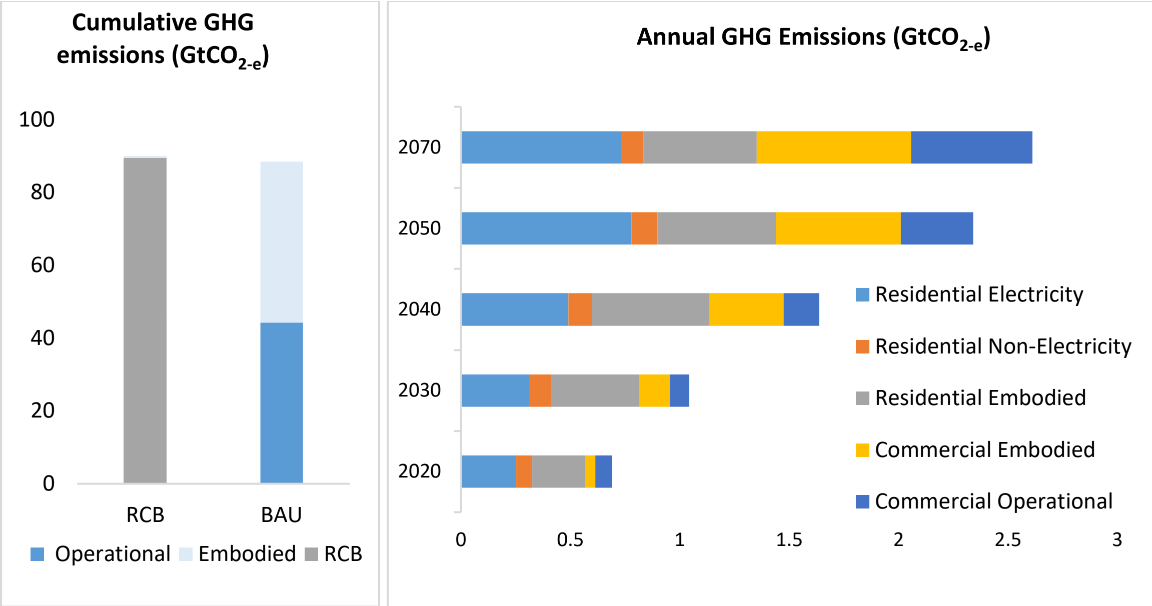
Emissions related to India's growing buildings sector may exceed its allocated carbon budget for 1.5 °C.

In the BAU scenario, the cumulative emissions (direct and embodied) from buildings between 2020 and 2070 are projected to reach 90.85 $GtCO_{2\text{-}e}$, exceeding the carbon budget allocated for India by 2%. In the absence of additional climate action, they would constitute 21% of India's total emissions in 2070.

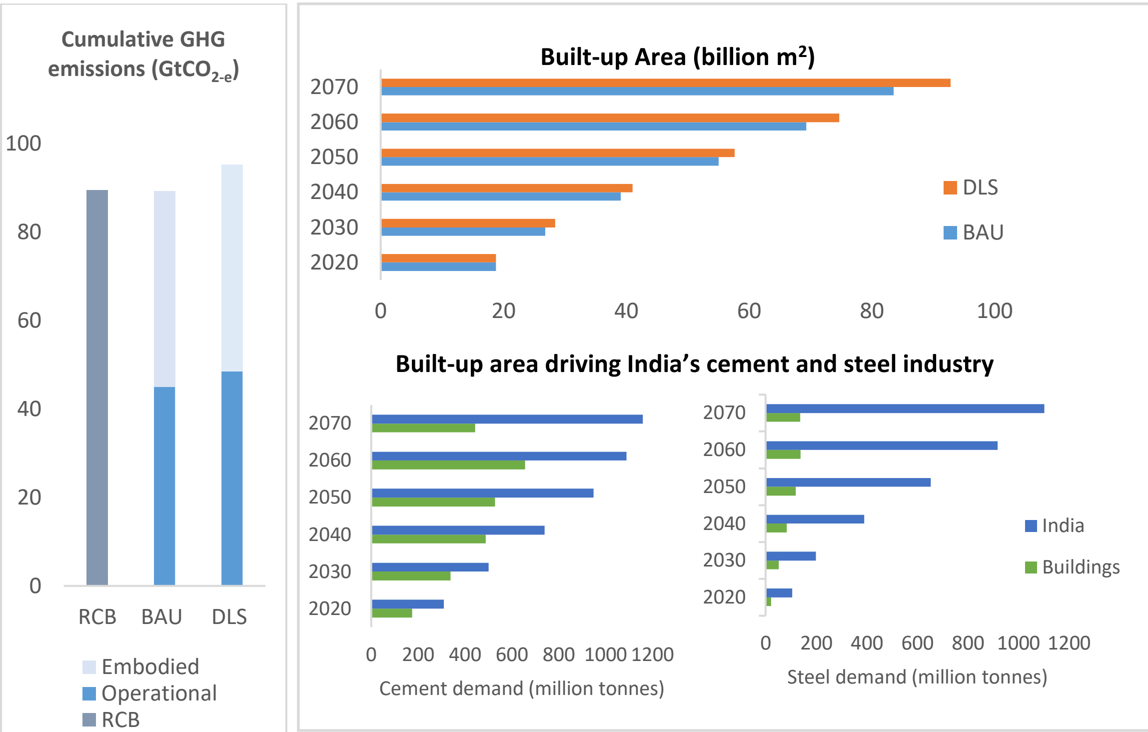
Achieving "decent living standards" will cause a further increase in emissions.

Accounting for efforts towards developmental goals such as achieving housing and clean cooking for all by 2030 and providing thermal comfort results in cumulative emissions of 97.11 GtCO2-e, overshooting the carbon budget by 8%, in the DLS scenario. In terms of gross built-up area, achieving "housing for all" results in a 10% increase over BAU by 2070.

[1] Total GHG emissions from the buildings sector includes direct cooking emissions, power sector emissions in meeting residential and commercial electricity demands, and embodied industrial emissions (from cement, steel, bricks, aluminium, and other alternative materials) for meeting building construction demand.



Business-as-usual scenario (BAU)

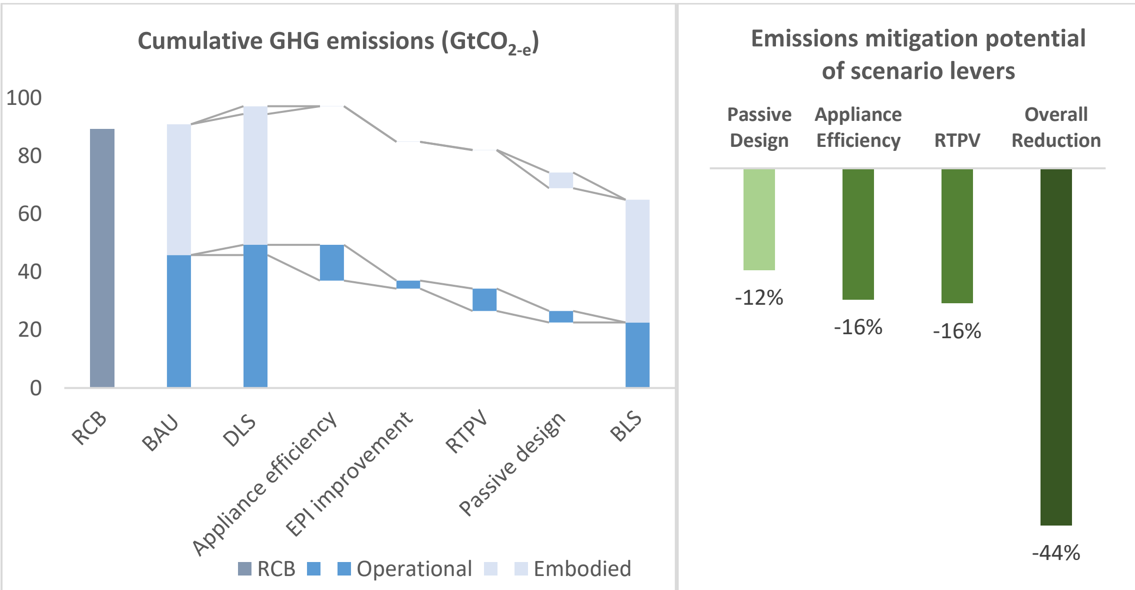


Decent-living-standards scenario (DLS)

Decarbonisation pathway led by stakeholders in the buildings sector can reduce up to 43% emissions

The BLS scenario envisions the impacts of interventions driven by behavioural changes, such as opting for cleaner cooking fuel and uptake of energy-efficient appliances and solar rooftop systems. This scenario also assumes achievement of decent living standards. By 2070, the annual embodied emissions can reduce by 16%, while the annual operational emissions can come down by 69%.

- Installation of rooftop photovoltaic systems: this alone holds a mitigation potential of 16%.
- Energy efficiency: Adoption of efficient appliances, combined with high uptake of electric (more efficient) cooking in both urban and rural areas, carries a 16% emissions reduction potential. This is already paced well due to government support. This intervention also includes improvement of energy performance index (EPI) of commercial buildings.
- Incorporation of passive design aspects: This has a potential to bring about 12% emissions reduction, along with meeting the requirements of thermal comfort and sustainable cooling.



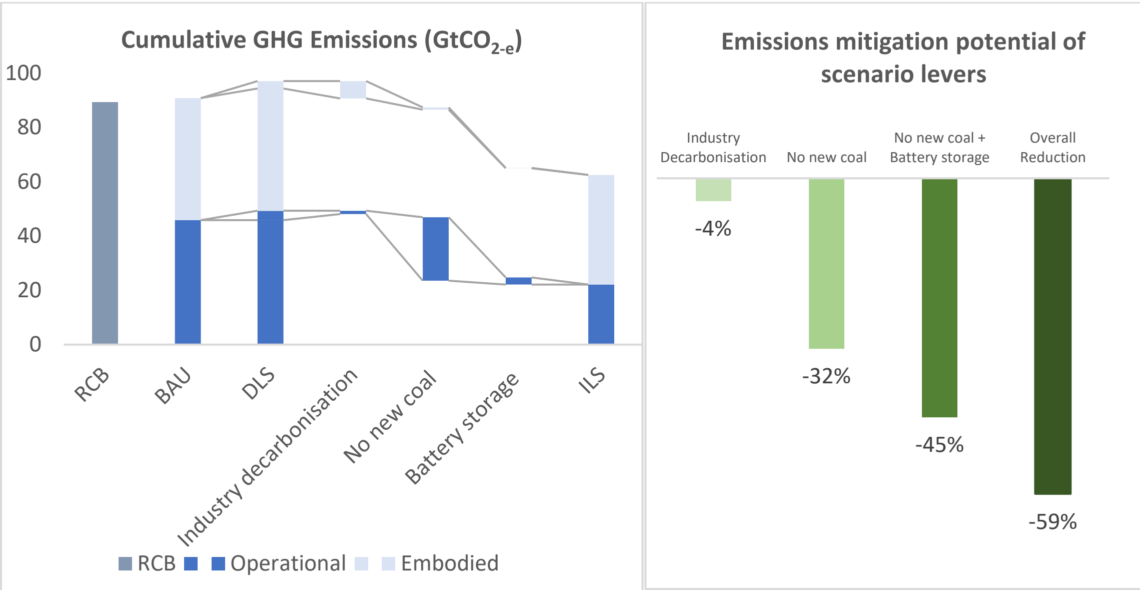
Buildings-led scenario (BLS)

Interventions in the industry sector alone have the potential to reduce up to 59% of emissions.

Given that the indirect emissions due to building materials and electricity consumption could constitute 30% and 50%, respectively, of the total sectoral emissions, industries and the power sector have a major role to play in decarbonising the sector.

No new coal-power-plants sanctioning after 2025: With a significant mitigation potential of 32%, this lever, when coupled with enhanced battery storage capacity, yields an overall mitigation potential of 45%.

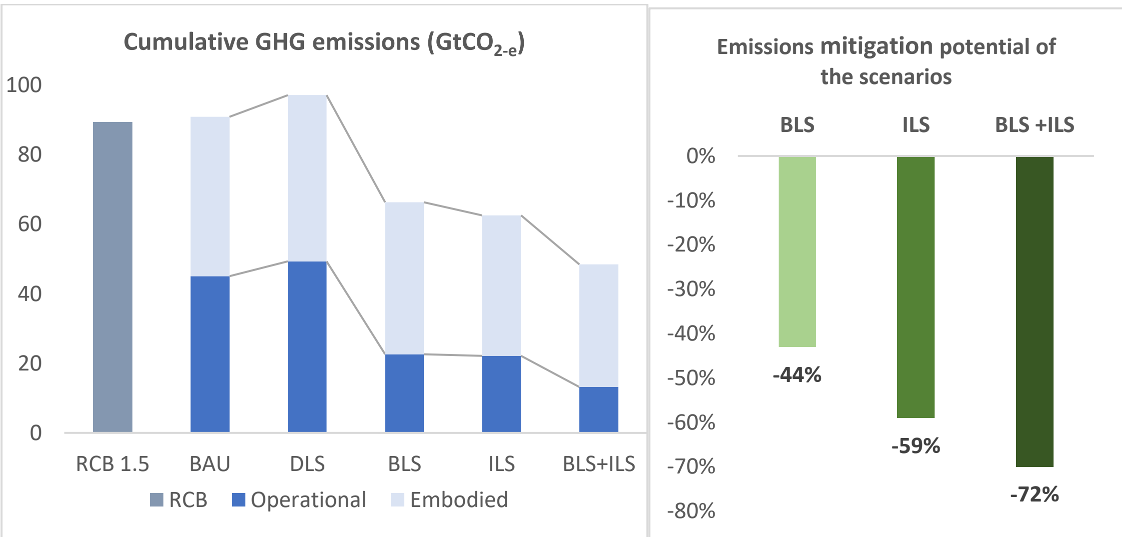
Fuel and process shifts in the manufacturing industry: Shifts in production processes, along with the use of alternative construction material and alternative fuels in the cement, steel, and aluminium industries also have a notable impact on emissions.



Industry-led scenario (ILS)

Pathway combining both most powerful in bringing down emissions

The integrated scenario (BLS+ILS) demonstrates the collective impact of 72% reduction in emissions and 47% reduction in energy demand in 2070, resulting in a substantial saving of 1.83 $GtCO_{2-e}$. This scenario utilises 54% of the allocated carbon budget, but even with such aggressive decarbonisation, emissions from the buildings sector do not reach net-zero levels. Carbon capture and storage (CCS) technologies (not included in this study) are essential for attaining net-zero emissions, particularly in the industrial sectors (cement, steel, bricks).

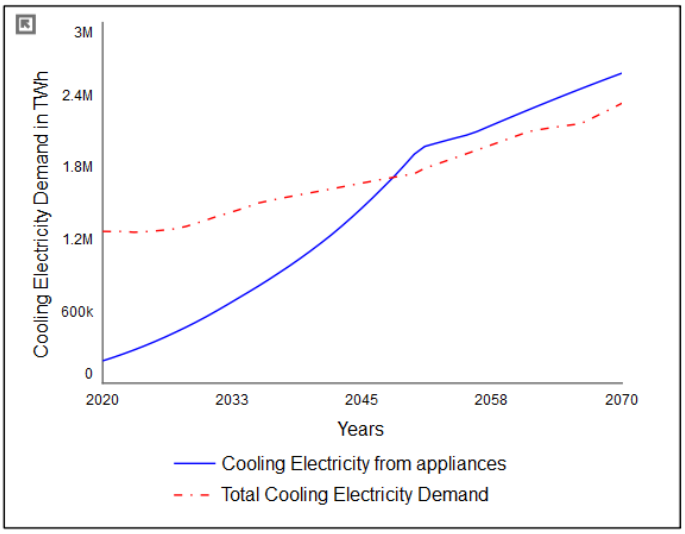


Integrated (BLS+ILS) scenario

Thermal comfort for all: Beyond AC/fan ownership

Cooling energy demand essentially drives the buildings energy/emissions story of India. Most modeling studies analyse cooling demand based on appliance ownership. SAFARI model allows the determination of thermal comfort requirement as a function of building envelope and construction choices.

We find that only 22% of the total thermal comfort requirements were fulfilled for the overall population in 2023, attributable to a low appliance-penetration rate of 7-10%. Assuming an increase in the ownership of air-conditioners with income growth, the cooling electricity demand from appliances will surpass the thermal comfort needs by 2050. This presents a substantial opportunity for energy savings, potentially achievable through regulatory shifts that incorporate thermal comfort considerations, which can eventually avoid 64.25 million $tCO_{2\text{-}e}$ in 2070. Further savings of 440 million $tCO_{2\text{-}e}$ are possible by adopting passive design aspects.



Cooling demand estimated with 'thermal comfort' considerations vs that based on appliance ownership

Contents

Tables

Figures

Abbreviations

AAC	Autoclaved Aerated Concrete block
AC	Air Conditioner
BAU	Business-As-Usual Scenario
BCB	Burnt Clay Brick
BEE	Bureau of Energy Efficiency
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BLS	Buildings-Led Scenario
CAPEX	Capital Expenditures
CCUS	Carbon Capture, Utilisation, and Storage
CEEW	Council on Environment, Energy and Water
COP	Conference of the Parties
CoPe	Coefficient of Performance Equivalent
CSTEP	Center for Study of Science, Technology and Policy
DLS	Decent Living Standards
EAF	Electric Arc Furnace
ECBC	Energy Conservation Building Code
ECSBC	Energy Conservation and Sustainable Building Code
EE	Embodied Energy
EEm	Embodied Emission
EF	Emission Factor
ENS	Eco-Niwas Samhita
EPI	Energy Performance Index
EV	Electric Vehicle
EWS	Economically Weaker Section
FA	Fly-Ash Block
FaLG	Fly-Ash-Lime-Gypsum block
FSI	Floor Space Index
GDP	Gross Domestic Product
GER	Gross Enrolment Ratio
GHG	Greenhouse Gas
GRIHA	Green Rating for Integrated Habitat Assessment

GtCO2-e	Giga Tonnes of Carbon-Dioxide Equivalent
HC	Hollow Concrete
HIG	High Income Group
HVAC	Heating, Ventilation, and Air Conditioning
ICAP	India Cooling Action Plan
IESS	India Energy Security Scenarios
IGBC	Indian Green Building Council
ILS	Industry-Led Scenario
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
LiFE	Lifestyle for Environment
LIG	Low Income Group
LPG	Liquefied Petroleum Gas
LST	Land Surface Temperature
MIG	Middle Income Group
NSS	National Sample Survey
NSSO	National Sample Survey Office
OECD	Organisation for Economic Co-operation and Development
OPEX	Operating Expenses
PMAY U/R	Pradhan Mantri Awas Yojana Urban/Rural
PV	Photovoltaic
RE	Renewable Energy
RETV	Residential Envelope Transmittance Value
RMC	Ready-Mix Concrete
RTPV	Rooftop Photovoltaic
SAFARI	Sustainable Alternative Futures for India
SC	Solid Concrete Block
SDG	Sustainable Development Goals
SEB	Stabilised Earth Block
SHGC	Solar Heat Gain Coefficient
TWh	Terawatt-Hours
UHI	Urban Heat Island
WWR	Window-to-Wall Ratio

1. Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) estimated the remaining global carbon budget[2] (2020 onwards) to be around 500 giga tonnes of carbon dioxide equivalent ($GtCO_{2\text{-}e}$) (IPCC, 2022) for a 50% chance of limiting global warming to 1.5 °C (above pre-industrial levels). Considering historical responsibilities, India's fair share of this global budget is estimated to be around 89 $GtCO_{2\text{-}e}$ by Climate Equity Monitor (Climate equity monitor, 2024). India—with burgeoning population and rapid urbanisation—is at a crossroads, striving to meet the fundamental need for housing and infrastructure and aspiring to realise decent living standards on the one hand, and going low-carbon on its path to net zero by 2070 on the other. The buildings sector, therefore, emerges as a critical focal point, for it drives emissions in the power and industrial (construction materials) sectors.

According to the Sustainable Alternative Futures for India (SAFARI) model (Kumar et al., 2021), the buildings sector currently constitutes (directly and indirectly) 30% of energy demand, and accounts for 25.6% of greenhouse gas (GHG) emissions. These numbers will increase further as most of the buildings that will exist in India in 2050 are yet to be built. This calls for taking individual as well as collective action towards conservation and meaningful resource utilisation as set forth in the Lifestyle for Environment (LiFE) mission, introduced by the Indian Prime Minister at the 26th session of the Conference of the Parties (COP26) (NITI Aayog, 2023).

The policy landscape in India adeptly manages the developmental aspirations of providing for housing and other infrastructure needs, through initiatives like the *Pradhan Mantri Awas Yojana* (PMAY). Simultaneously, the challenges posed by increasing temperatures and heatwaves are being addressed through the India Cooling Action Plan (ICAP). At the same time, there is a concerted effort to drive decarbonisation initiatives like the Green Rating for Integrated Habitat Assessment (GRIHA), the Energy Conservation Building Code (ECBC), the upcoming Energy Conservation and Sustainable Building Code (ECSBC), and *Eco-Niwas Samhita* (ENS), which zeroing in on minimising operational carbon. However, a notable gap exists with regard to policies addressing embodied carbon, posing a roadblock to comprehensive emission reduction in the sector. This gap assumes significance especially in view of the anticipated surge in new construction over the coming decades. Efforts are needed to develop a policy structure informed by dedicated interventions to control embodied emissions as well, which is otherwise quite challenging. Therefore, to steer the sector towards a net-zero trajectory, a comprehensive approach addressing the overall carbon emissions should be adopted.

Through this report we present different pathways for reducing overall carbon emissions in India's buildings sector, focussing on the goal of attaining net-zero emissions within the sector by 2070.

[2] A carbon budget refers to the allowable amount of carbon dioxide emissions that can be released into the atmosphere while keeping global warming within a specified limit, typically aiming to prevent a temperature increase beyond 1.5 °C or 2 °C above pre-industrial levels.

2. Approach and Modelling Framework

2.1. Modelling logic

This study aims to map out the potential decarbonisation pathways for India's buildings sector till 2070, using SAFARI—a system dynamics simulation model. Emphasising the imperative of aligning India's developmental goals across diverse economic sectors, SAFARI factors in select development goals, such as housing for all, healthcare for all, etc., in addition to crucial socioeconomic parameters like population dynamics and gross domestic product (GDP). Data on population and GDP are exogenously fed into the model, considering population projections from World Population Prospects, 2019(UN-DESA, 2019), and basing the GDP growth rates on the India Energy Security Scenarios (IESS) (NITI Aayog, 2015) and the Organisation for Economic Co-operation and Development (OECD) databases (Dellink et al., 2017).

SAFARI follows a bottom-up approach, offering a nuanced understanding of sectoral interdependencies and the intricate trade-offs to balance developmental goals with climate-conscious actions. The growth in buildings sector is primarily driven by the demands arising from the goals of 'housing for all', 'healthcare for all', 'education for all', and 'thermal comfort for all', which is hampered by the constraints related to water, land, and materials. The implications of meeting the increasing demand for infrastructure and decent living standards have a profound impact on both energy consumption and emissions. This impact is twofold: first, through the material requirements and construction of new buildings stock, contributing to the embodied effects (which are essentially one-time occurrences); and second, through the ongoing operational aspects of buildings usage, which compound annually and significantly contribute to long-term energy consumption and emissions. In essence, SAFARI not only addresses the immediate effects of construction but also takes into account the sustained impact of buildings in their operational phase, thereby offering a comprehensive understanding of the entire life-cycle of infrastructure development. Figure 1 presents the causal loop diagram of the buildings sector, along with the interlinkages.

2.2. Interlinkages with other sectors

2.2.1 Industries

The demand for construction materials interacts with the cement and steel segments of the industries module. This, in turn, is limited by material availability which drives the possible construction rate. Simultaneously, the industry module internally increases cement and steel production to meet excess demand beyond its existing capacity. Also, the water demand for construction, derived from the intended housing construction rate, interacts with SAFARI's water module, offering insights into the available water resources. The relationship between the desired and actual construction rates for cement, steel, and water is as follows (Kumar et al., 2021):

$$\text{Actual construction rate} = \text{Min}\,(\text{Desired construction rate}, \text{Possible construction rate}) \qquad (1)$$

Where, the desired construction rate is the number of houses to be constructed per year, based on housing sanction rate (historically adopted from PMAY scheme).

The possible construction rate is the minimum number of houses that can be constructed depending on cement, steel, and water availability (Kumar et al., 2021).

$$Possible\ construction\ rate = \\ Min\ \left(\frac{Cement\ Availability}{Cement\ required\ per\ house}, \frac{Steel\ Availability}{Steel\ required\ per\ house}, \frac{Water\ Availaibility}{Water\ required\ per\ house}\right) \quad (2)$$

$$Cement/steel/water\ availability\ = \\ Min\ (Resource\ demanded, Resource\ produced) \quad (3)$$

The demand for cement and steel is also impacted by the structural block combination requirements, described ahead in the material section.

2.2.2 Land

The net land required to accommodate the combined built-up area of residential and commercial buildings is governed by the built form connected through floor space index (FSI). The interaction of land module with buildings is not exhaustively addressed in SAFARI due to data challenges. However, we consider this as a forward-looking initiative to investigate the consequences of built density under various FSI scenarios on land usage.

2.2.3 Power Sector

Power sector linkages are established through electricity demand and consumption. A lower emission factor from grid supply tends to reduce operational emissions from the sector. Moreover, a higher penetration of renewable sources and nuclear power into the energy mix will generate clean power to fuel appliances like heating, ventilation, and air conditioning (HVAC) systems, resulting in reduced emissions.

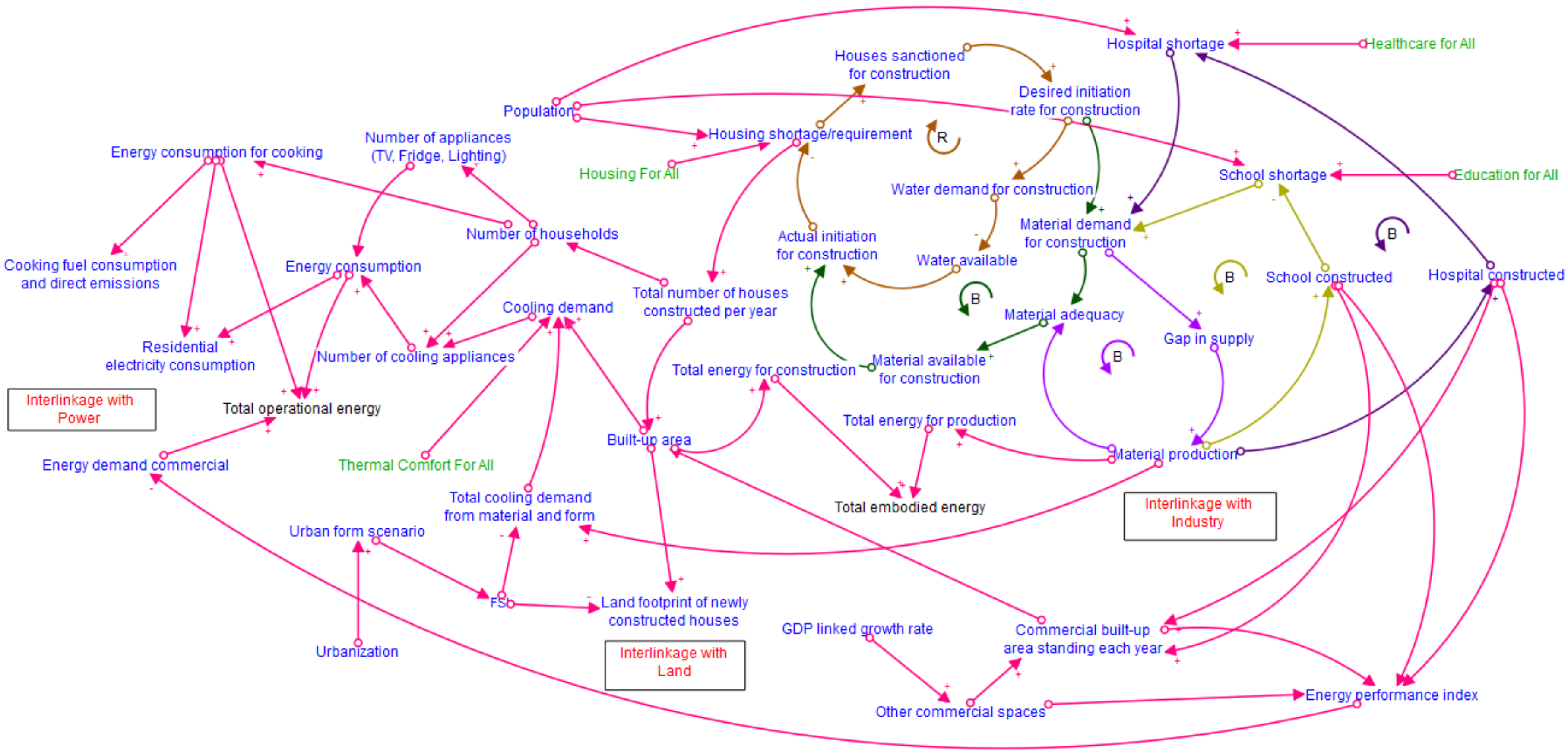


Figure 1: Causal loop diagram for buildings sector in SAFARI

2.3. Methodology Adopted for buildings-sector modelling

2.3.1 Residential

The residential buildings sector in SAFARI includes housing shortage, new housing stock required to meet the shortage, material demand arising from new stock, energy consumption from appliances and cooking fuel, building design aspects addressing thermal comfort requirements, and rooftop photovoltaic (RTPV) integration. Interventions within these modules are implemented to reduce operational emissions by transitioning to efficient appliances and facilitating access to clean cooking. Simultaneously, efforts are directed towards reducing embodied emissions by encouraging the use of low-carbon materials.

A. Housing for All

This goal is based on PMAY, which aims to provide affordable housing to urban and rural population. In accordance with this, SAFARI evaluates housing shortages on the basis of income levels—economically weaker section/low-income group (EWS/LIG) and middle-income group/high-income group (MIG/HIG) in urban areas. The population projections for the respective urban categories are made on the basis of EWS/LIG to MIG/HIG population ratio, taken as 3:1 for 2011, which will reach 1:1 by 2050. The historical sanction rates are adjusted in accordance with the PMAY–U and PMAY-R rates for EWS/LIG and rural housing, respectively, and projected on the basis of the dynamic housing shortage to meet the housing target by 2030. The model also examines shortage-filling and reconstruction for MIG/HIG households.

The data for the existing housing stock is sourced from the National Sample Survey (NSS) 65th Round on Housing Condition and the Technical Group on Urban Housing Shortage reports (Ministry of Housing & Urban Poverty Alleviation, 2011; NSSO, 2016) with the base year set at 2011. The existing housing stock, derived from these sources for both urban and rural areas, is then categorised into the following age groups: less than 1, 1–5, 5–10, 10–20, 20–40, 40–50, 50–60, 60–80, and more than 80 years. The structural conditions of the existing houses within each age group are classified as good, satisfactory, or bad. For the new stock projected by the model, housing stock that is structurally good in condition, with age groups 0–30 years and 30–50 years, is considered.

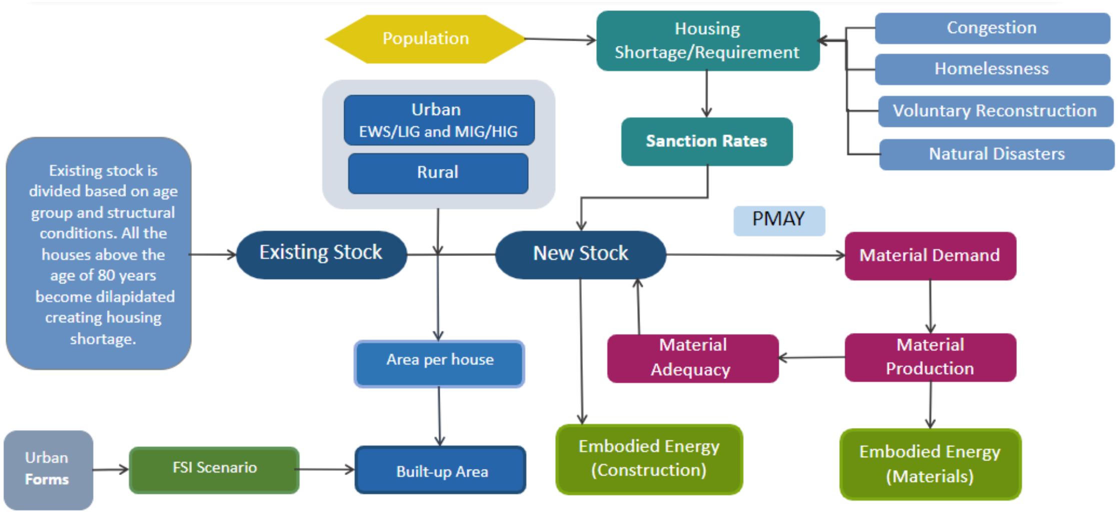


Figure 2: Methodology for estimating housing shortage and construction requirement

Additionally, the housing shortage is driven by the factors described below:

Obsolescence/Dilapidation: As houses advance through their life-cycles, they become dilapidated, contributing to housing shortage. In this model, the shortage arising from aging housing stock includes:

- All houses that are more than 80 years old and all houses between 40 and 80 years of age that are structurally in a bad condition (considering the existing housing stock of 2011).
- All newly constructed houses that will become a part of the aging housing stock once they reach the age of 50 years.

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 (Ministry of Housing & Urban Poverty Alleviation, 2011).

Homelessness is estimated to be around 0.53 million for urban and 0 for rural areas (Ministry of Housing & Urban Poverty Alleviation, 2011).

Others:

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

The calculation of the total built-up area considers the existing housing stock, the additional houses for meeting shortages, and the average built-up area for each housing category. SAFARI also incorporates a rising trend in average built-up area per household and a decline in household size—from 4.9 to 2.88 persons per household for urban (de la Rue du Can et al., 2019) and from 4.9 to 3.66 for rural HH by 2050 (NITI Aayog, 2015)—which is associated with increasing income levels and better living standards. The specific built-up area considered for each housing type is detailed in Table 7 of the Appendix.

B. *Material Demand*

The materials considered for constructing the required houses consist of seven types of structural blocks—burnt clay brick (BCB), hollow concrete block (HC), solid concrete block (SC), fly-ash block (FA), fly-ash-lime-gypsum block (FaLG), autoclaved aerated concrete block (AAC), and stabilised earth block (SEB). These were selected on the basis of their alignment with current usage trends, policy support in the form of viable alternative housing materials, technological availability (especially for newer materials), embodied energy efficiency, and material economy considerations (Bansal et al., 2014; Bureau of Energy Efficiency, 2018; Sabapathy & Maithel, 2013; Venkatarama Reddy & Jagadish, 2003). In addition, SAFARI accounts for cement, steel, sand, aggregate, water, and energy demands for construction (NITI Aayog, 2015; Reddy & Jagadish, 2003; R. Singh et al., 2014). The embodied energy (EE) and emissions (EEm) values used are described in Table 8 of the Appendix.

Total quantity of material required is computed as:

$$M_i = M_a \times (P_{\%} \times A) \tag{4}$$

Where, M_i = Total required quantity of each material

M_a = Material requirement per (square meter) m^2 of floor area

A = Residential built area

$P_{\%}$ = Percentage of floor area under each material

Each building block has an associated material requirement per m^2 of floor area. The total quantity of cement, steel, sand, and aggregate required annually is the sum of the amount of these materials associated with each building block.

Total cement (C)/steel (St)/sand (S)/aggregate (Ag) required is computed as:

$$\sum_i^n (C_{ai}/St_{ai}/\ S_{ai}/Ag_{ai} \times (P_{\%i} \times A)) \tag{5}$$

Where, $C_a/St_a/S_a/Ag_a$ is the material requirement per m^2 of floor area of each of the seven blocks (i = 1 to n). A 5% cement wastage was assumed and added to the total computed cement requirement.

Aluminium demand has been estimated considering the requirement per m^2 of plinth area and the number of houses to be constructed.

The total EE and EEm of all materials are computed as:

$$EE = \sum_i^n (M_i \times\ e_i) \tag{6}$$

$$EEm = \sum_i^n (M_i \times\ EF_i) \tag{7}$$

Where, M_i is the required quantity of each material; e_i is the embodied energy of respective blocks; and EF_i is the emission factor of respective blocks.

Additionally, alternative construction technologies like Mivan shuttering—widely employed in the production of affordable housing under the PMAY scheme in India—have been considered. Keeping in view the ongoing trends and the growth-rate forecasts, a certain percentage of new houses is presumed to be built using these technologies, each with distinct requirements for cement, steel, aluminium, and ready-mix concrete (RMC). The material requirement per unit has been determined by referring to the existing literature (as given in Table 9 of the Appendix), and the total quantity needed has been computed.

C. Cooking and Appliances

Cooking

Cooking energy is calculated on the basis of different types of fuels such as liquefied petroleum gas (LPG), electricity, pressurised natural gas, biomass, and others that include coal, kerosene, and biogas, and their emissions across all urban and rural households. The formula for calculating the demand for cooking energy is:

$$Cooking\ energy\ from\ fuel\ =\ No.of\ households\ using\ fuel\ \times\ Average\ useful\ cooking\ energy\ required\ per\ household / \ Efficiency\ of\ fuel \qquad (8)$$

For the calculation:

1. the 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. The historical percentage share of fuel-type data has been sourced from the documents of IESS (NITI Aayog, 2015) and Council on Environment, Energy and Water (CEEW) (Mani, et al., 2021) are calibrated accordingly;
2. the cooking efficiency data for different fuels has been taken from IESS (NITI Aayog, 2015);
3. useful cooking energy has been assumed to be 7.09722e-7 terawatt-hours (TWh), in accordance with a CEEW report (Mani et al., 2021);
4. fuel emissions have been calculated by multiplying fuel-wise cooking energy with the emission factor of that fuel.

Appliances

The energy consumption of each appliance has been calculated for urban and rural households by multiplying the total number of appliances, hours of use, power consumption, and efficiency of appliances, as shown in Figure 3.

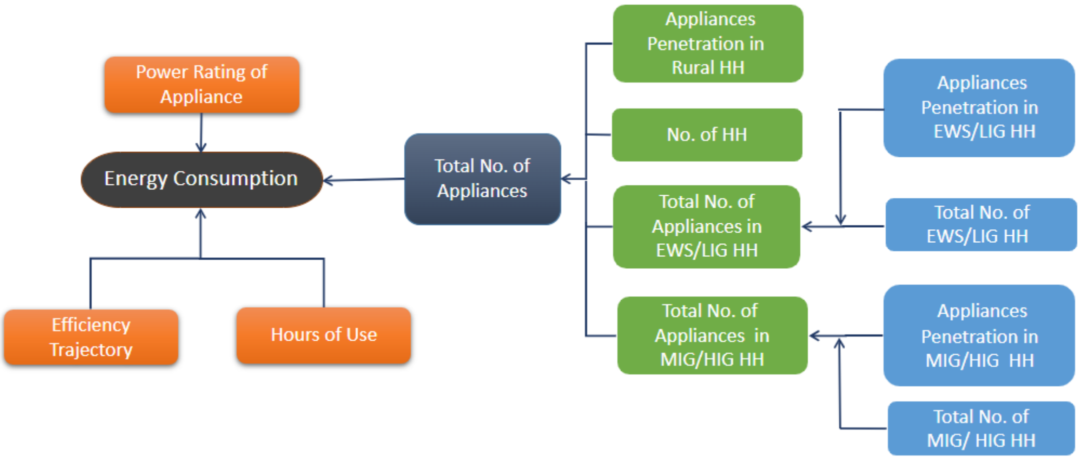


Figure 3: Methodology for estimating appliance energy consumption

The appliances considered in the model are television, fridge, fan, air conditioner (AC), and lighting devices (NITI Aayog, 2015). The formula for appliance energy consumption is:

$$\text{Total number of appliances} \times \text{Hours of use} \times \text{Power consumption} \times \text{Efficiency of appliance} \qquad (9)$$

For the calculation:

1. the number of households and appliance penetration for urban and rural households have been considered to arrive at the number of appliances, wherein the penetration values have been adopted from IESS (NITI Aayog, 2015);

2. power rating is classified as low, medium, or high on the basis of the energy efficiency of the appliance, which is sourced from IESS (NITI Aayog, 2015);

3. each appliance has four different efficiency trajectories—A, B, C, and D. Each efficiency trajectory has different proportions of low- and high-efficiency appliances, wherein the share of high-efficiency appliances increases by 0.3%, 17%, 28%, and 86% for A, B, C, and D, respectively, by 2070. The four efficiency trajectories are shown in Table 10 of the Appendix.

Cost of transitioning to high-efficiency appliances

The cost of transitioning to high-efficiency appliances is inclusive of capital expenditures (CAPEX) and operating expenses (OPEX). The cost is calculated for all four efficiency trajectories of different appliances, considering their life-cycles. CAPEX costs are estimated using the cost of appliances sourced from IESS (NITI Aayog, 2015), while the calculation for OPEX costs is based on the average electricity tariff rates for Tier-1 and Tier-2 cities, and rural towns, as sourced from tariff booklets. A declining discount rate is used to evaluate the net present value of CAPEX and OPEX and applied to the cumulative cost. The cumulative cost is discounted at a rate of 3% until 2040, and at a rate of 2% for the period 2040–2070. The declining discount rate has been employed to account for the uncertainty over longer durations (Weitzman, 1998). The difference between the total costs for low-efficiency and high-efficiency trajectories (including discounted rates over the modelling timeframe) indicates cost savings.

D. Thermal Comfort for All

The cooling demand for both urban and rural households is calculated by adding the cooling demand arising from sensible heat (heat gain due to the changing inside and outside temperatures; occurs through buildings envelopes and roofs) and latent heat (heat gain due to humidity) (Figure 4). The sensible-heat-gain load is calculated for walls and roofs and the latent-heat-gain load is calculated using the latent heat-gain coefficient from ENS 2018 (Bureau of Energy Efficiency, 2018). The total cooling load is calculated by assuming two reference setback temperatures—26 °C and 28 °C —for adaptive thermal comfort (Maithel et al., 2020).

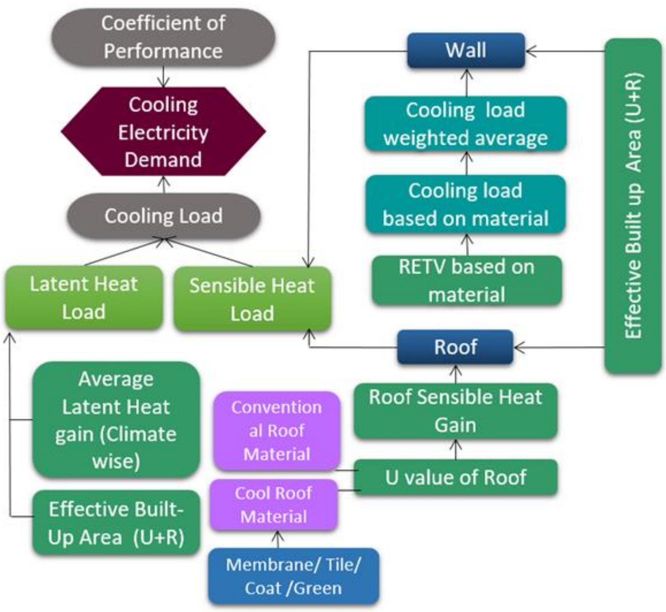


Figure 4: Methodology for estimating cooling electricity demand

Sensible heat gain: Cooling demand from building envelopes

This is calculated using the residential envelope transmittance value (RETV) formula adopted from ENS 2018 [3](Bureau of Energy Efficiency, 2018), as follows:

$$RETV = \frac{1}{A_{envelope}} \times \left[\left\{a \times \sum_{i=1}^{n}\left(A_{oppaque_i} \times U_{oppaque_i} \times \omega_i\right)\right\} + \left\{b \times \sum_{i=1}^{n}\left(A_{non-oppaque_i} \times U_{non-oppaque_i} \times \omega_i\right)\right\} + \left\{c \times \sum_{i=1}^{n}\left(A_{non-oppaque_i} \times SHGC_{eq_i} \times \omega_i\right)\right\}\right] \quad (10)$$

The variables in the RETV formula carry the same meaning as defined in the ENS code. Fifty per cent of the built-up area is considered to be in the warm and humid zone and the rest is in the hot, dry, and composite zones. As India has a very small area under temperate zone, it is considered as negligible for the calculation. Weighted averages have been taken for orientation and latitude factors to provide a relevant estimate for the national scale, and window-to-wall ratio (WWR) values have been assigned, based on the two climate zones[4]

[3] ENS 2018 (Part 1) is a code developed by BEE to set minimum standards for buildings envelope performance and to ensure adequate natural ventilation and daylight potential for energy-efficient residential buildings.

mentioned above. Further, the RETV values have been calculated for all material blocks considered for the study and for alternative construction technology, while the weighted average values for RETV have been calculated on the basis of the percentage share of material and construction type. Subsequently, RETV has been converted into a cooling load by applying linear regression from the energy simulation model [19].

Sensible heat gain: Cooling demand from roofs

Cooling demand from roofs is arrived at through the linear regression of thermal transmittance due to roofs, which is calculated using the formula sourced from ENS 2018 (Bureau of Energy Efficiency, 2018):

$$U_{roof} = \frac{1}{A_{roof}} [\sum_{i=1}^{n} (U_i \times A_i)] \tag{11}$$

The variables carry the same meaning as assigned to them in the ENS code. Considering the scale of the study, an aggregate U value based on different materials from all states is derived for the rural and urban data sourced from Census 2011 (National Buildings Organisation, Ministry of Housing and Urban Poverty Alleviation, 2013). The average height considered for obtaining roof area is 1.25 floors for rural areas. The number of floors for urban areas is dependent on the FSI scenarios for urban households, which are segregated into low-FSI and high-FSI scenarios, wherein the latter includes scenarios of mixed building heights ranging from less to more compact urban forms.

Latent gain

Energy simulations were performed for calculating latent loads for different climatic zones, using the energy simulation model [21]. The latent load per unit of built-up area obtained from these simulations was kept the same for urban and rural areas and constant for the modelling time horizon. The total cooling load is calculated by adding sensible- and latent-heat gains.

Coefficient of performance equivalent (CoPe)

The coefficient of performance equivalent (CoPe) indicates the efficiency of the cooling technology used. It is considered to be 2.75 for MIG/HIG households and 2 for EWS/LIG households until 2020 (Maithel et al., 2020). This is assumed to gradually increase at the rate of 2% per annum, reaching a maximum of 5% for MIG/HIG households and 3.5% for EWS/LIG households by 2070. The total cooling load is divided by the COPe to arrive at the total cooling electricity demand.

E. Rooftop Photovoltaics (RTPV) for Buildings:

The analytical model focusses on solar rooftops for rural and urban residential and commercial buildings. The primary parameters for energy calculation from RTPV across all building types include the total built area and the number of floors. Additionally, crucial factors influencing RTPV energy generation encompass solar radiation (kWh/m²/year), RTPV adoption rate (%), conversion efficiency of RTPV (%), and the utilisable surface area of buildings for RTPV.

$$Energy\ from\ RTPV = \left((Utilisable\ exposed\ surface\ of\ buildings\ for\ RTPV) \times \text{roof area}\right) \times RTPV\ adoption\ rate \times solar\ radiation \times conversion\ efficiency\ of\ RTPV \tag{12}$$

The data for total installed capacity of RTPV in India for the period 2015 to 2022 is taken from the annual reports of Ministry of New and Renewable Energy (MNRE) and the ultimate rooftop potential by 2050 for India projected by National Renewable Energy Laboratory (NREL) is considered for calculation (Das, 2022). The RTPV adoption rate is calculated using RTPV generation based on the NREL installed capacity potential data and buildings electricity demand data. The projected installed capacity for 2050 is 419 GW and by 2070 it will reach 552 GW.

India has a vast potential for solar power generation, as about 58% of the total land area (1.89 million km^2) receives an annual average insolation above 5 kWh/m^2/day (Ramchandra, 2011). Considering an average daily radiation of 5 kwh/m^2/day, the annual solar radiation has been calculated as 1830 kwh/m^2/year. Energy calculations have been performed for rural and urban households, considering the FSI scenarios.

Due to the considerable advances in photovoltaic technology over recent years, the average panel-conversion efficiency has increased from 15% to over 22% (Svarc, 2023). Therefore, the conversion efficiency of RTPV is assumed to be 20% in this study. As per our expert consultations, at least 20–30% of rooftop area is required to generate electricity for meeting the demand of an average household. So the usable exposed surface area of buildings for RTPV is assumed to be 20%.

2.3.2 Commercial buildings

In this section, we discuss our approach for predicting the built-up area for commercial buildings and the calculation of embodied and operational emissions. The total built-up area of commercial buildings has been divided into three categories (goal-driven, business-driven, and infrastructural) for a refined analysis of the buildings sector, considering technological and policy interventions in each sector.

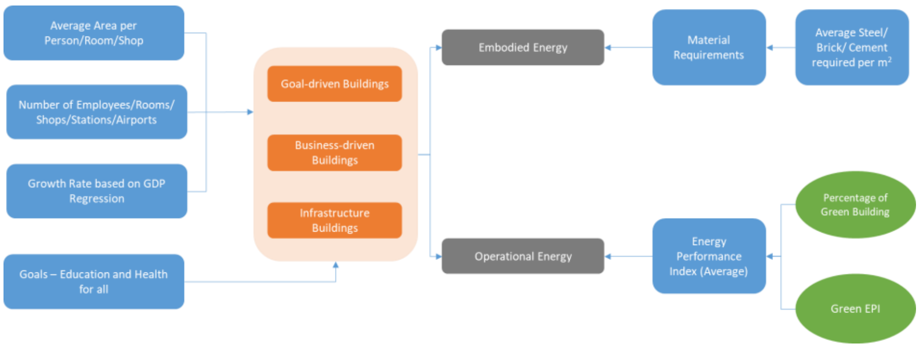


Figure 5: Modelling approach for estimating energy demand from commercial buildings

The archetype approach informs the modelling of commercial buildings by defining fundamental parameters, as illustrated in Figure 5, to constitute the total built-up area of three distinct categories based on the Sustainable Development Goals (SDGs), business growth, and infrastructure parameters. Operational energy is calculated based on the energy demand, which are driven by the energy performance index of each subcategory of buildings. A lever was developed to lower operating emissions in order to take into consideration the influence of green buildings in each subcategory. With the help of this lever, the Energy Performance Index (EPI) values—which are determined by subcategory variations in the percentage of green buildings and green building standards—are improved. Further, embodied emissions are predicted by deriving the major building materials per unit to arrive at total material requirements and related embodied emissions from production and manufacturing, using the interlinkages of SAFARI

Total built-up area

Predicting the total built-up area of commercial buildings at a national level is a complex task due to the unprecedented growth of buildings and unorganised settlements around the suburbs of major cities. The most recent study on building footprint was conducted by Alliance for an Energy Efficient Economy (AEEE) (Kumar, S et al., 2017) and IESS (NITI Aayog, 2015).

In this study, building typologies were derived based on their form and function. The demand for goal-driven buildings arises from the SDGs for providing healthcare and education to all in India. On the other hand, the business-driven and infrastructure buildings are categorised based on the basis of a simple calculation of the number of employees, shops, stations, airports, and corresponding area required as per national standards and guidelines. Using these parameters, the historical built-up area was predicted.

The growth of built-up area is projected by deriving the elasticity of built-up area with respect to India's GDP, using regressions. Gross value added and gross output data for hospitality, transit, and other non-residential buildings construction sectors were obtained from the Reserve Bank of India`s analysis of capital , labour , energy , materials , and service inputs database and National Account Statistics to facilitate regression analysis.

Total emissions

The total emissions are estimated by computing the embodied and operational emissions emerging from all building typologies. For calculations of operational energy, the EPI has been considered in accordance with the energy benchmarks published by the Bureau of Energy Efficiency (BEE) for different building typologies. Further, the EPI has been normalised for the different climate zones, as approximately 50% for warm & humid, and 50% for hot & dry and composite combined (Kumar et al., 2021).

Calculations for embodied energy for buildings are based on the ‘cradle-to-gate’ scope, as per the ISO 14044 standards (International Organization for Standardization [ISO], 2006), with a focus on subtypes A1 and A3. To estimate the upfront carbon emissions from the buildings sector, major building materials like steel, cement, brick, and aluminium have been considered for the study, with the main goal of arriving at informed approximations that are in the vicinity of embodied emissions per sector.

A. Goal-driven

The goal-driven category comprise of different types of commercial buildings in healthcare and education sectors. A bottom-up approach was used in SAFARI, where demands arising from the need to achieve the SDG for healthcare and education are the main drivers of growth (Ashok et al., 2022).

Healthcare and education goals focus on constructing hospitals to meet the required beds per capita and schools to achieve gross enrolment ratio (GER) targets, respectively. For these sectors, the operational requirements are assumed to remain consistent with historical investment trends of about 10–11% growth per annum, whereas the construction activities for creating the physical infrastructure needed to meet these goals are carried out by doubling investments in construction and allied manufacturing. This corresponds to the sectoral construction growth volume for the education and health infrastructure from the SAFARI model (Ashok et al., 2021).

The energy demand for hospitals was estimated on the basis of EPI values from the ECO Bench study (Sarraf et al., 2014) and BEE benchmarks (UNDP-GEF-BEE, 2020). These values were further modified on the basis of the different subcategories mentioned in Table 1. For educational buildings, due to the unavailability of any benchmark EPI, different case studies were reviewed and assumptions were made in accordance with the data from AEEE (Kumar, S et al., 2017).

Table 1: Goal-driven category and subcategories

Building type	Subcategories
Education	Elementary
	Secondary
	Senior Secondary
	Tertiary
Healthcare	Sub-Centre
	Primary Health Centre
	Community Health Centre
	District Hospitals
	Nursing Homes
	Big Hospitals

The embodied energy for educational buildings is determined by the amount of construction material required to build adequate schools and colleges to meet GER, whereas for hospital buildings it is based on the construction of adequate healthcare centres meeting the target of 3.5 beds/1,000 people.

B. Business-driven

According to projections by (PTI, 2022), India`s urban population will number 675 million by 2035 and is predicted to increase at the same rate in the years to come. Urbanisation and human settlements will create better opportunities for business and infrastructural advancements in the country. We have attempted to predict the upcoming built-up area and the total emissions arising due to this development, in the form of operational and embodied emissions.

The study analysed the growth patterns and environmental impact of three categories: hospitality, retail and office. Each sector was further divided into subcategories, as shown in Table 2. Historical data was collected from multiple sources, including the annual reports of the Federation of Hotel & Restaurant Associations of India (for the hospitality buildings), which provided data on the number of rooms and average room size per star category. For office buildings, the number of employees and the average area required per person were used as input parameters. It was found that nearby stores, such as *kirana*[5] stores,

[5] Kirana stores are small local shops (corner stores or convenience stores) that sell various food items and daily necessities.

supermarkets, and hypermarkets contribute significantly to the built-up area of business-driven buildings. The study highlights the significant role played by these sectors in the rapid urbanisation and unorganised development across the country.

The energy required by each sector was determined by referring to the EPI benchmark document by BEE for hotels, offices, and shopping malls. For the remaining subcategories, calculations were based on case studies and expert consultations. The future built-up area of each sector was determined on the basis of the regression analysis of GDP and the growth rate of individual sectors. Material requirement and energy demand were used as drivers to estimate the embodied and operational emissions.

Table 2: Subcategories of business-driven sectors

Sr. No.	Building Type	Subcategories
1	Hospitality	Below 3 stars Above 3 stars Others
2.	Office	Public Private Others
3	Retail	Unorganised Organised Hypermarts

C. *Infrastructural*

India is currently ranked 70 out of 140 countries for infrastructure quality in a global competitive index (Schwab & Zahidi, 2020). Infrastructure can be broadly categorised into utility and transportation infrastructure.

Table 3: Subcategories of Infrastructural Buildings

Sr. No.	Category	Subcategories
1	Airports	International Domestic
2	Railways Stations	Suburban Non suburban Halt stations
3.	Metro Stations	Halts stations Interchange stations

For this study, we have considered the major commercial buildings that are a part of transportation infrastructure (like railway stations, metros, and airports) under this sector. The goal was to arrive at an accurate approximation for this vast built-up area. The average size of platforms, stations, and circulation area for each person was determined using various sources, as mentioned in Table 3. During research, it was observed that major infrastructural projects were incorporating the environmental norms to reduce emissions and had a plan to reduce their operational emissions. For instance, railways and airports were found to be leading the path of decarbonisation by committing to reduce emissions by 2030, raising the standards every year to meet their targets.

The EPI considered is based on the data from Indian Green Building Council (IGBC) and Leadership in Energy and Environmental Design (LEED) case studies. The percentage of green buildings was estimated on the basis of sector-specific contribution towards green building certifications, with hospitality showing the highest percentage and retail having the lowest percentage. The savings potential per sector was estimated independently, taking into consideration the savings from star-rating standards available for selected sectors. For the remaining sectors, case studies of building code compliant buildings were considered.

3 Scenario Development

For developing a roadmap for decarbonising the building sector, we have explored five scenarios. Of these, the business-as-usual and decent-living-standards scenarios are centred on the current trends and developmental pathways, while the remaining three are shaped by aggressive decarbonisation strategies. The scenarios are discussed below:

1. **Business-as-usual scenario (BAU)**: This is a reference scenario that resembles the current growth trajectories of sectors and includes current policies which target climate action, but no additional aggressive decarbonisation interventions are included.
2. **Decent-living-standards scenario (DLS):** This scenario considers the developmental goals of the country, such as housing, education, healthcare, and improved living standards that attain thermal comfort through high uptake of cooling appliances. Therefore, this scenario signifies increased consumption while sustaining the current climate action policies. This scenario does not include aggressive decarbonisation interventions.
3. **Buildings-led scenario (BLS)**: This scenario includes aggressive decarbonisation scenarios, but only those that are within the buildings sector, such as the ones with higher percentage share of low-carbon cooking fuels, inclusion of rooftop photovoltaics, and use of low-carbon building materials. These interventions are mostly related to changing consumer behaviour and hence can be seen to be in alignment with Mission LiFE.
4. **Industry-led scenario (ILS):** This scenario includes aggressive decarbonisation scenarios from the industry and power sectors that simultaneously impact the buildings sector, such as inclusion of low-carbon cement and adoption of sustainable ways of manufacturing steel.
5. **Buildings & industry-led scenario (BLS + ILS)**: This scenarios combines the interventions of both buildings and industry sectors, creating a larger range of impact on buildings energy and emissions.

The detailed explanation of the interventions for the different scenarios is given in Tables 4 and 5.

Table 4: Interventions for BLS

Section	Interventions	Description
Residential Sector		
Cooking	Cooking-Fuel Share	100% electrification in urban households and 70% in rural households, with the phasing out of biomass, PNG, and others by 2070.
Appliance	Appliance-Efficiency Trajectory	Uptake of high-efficiency appliances.
Thermal Comfort	Passive Aspect	• The percentage share of efficient WWR (based on climate type) is adopted for 70% of the buildings. • The available roof space is completely converted to cool roof with 100% material share for green roof by 2070.

		• 100% buildings will adopt wall insulation; double-glazing low-emissivity glass is considered for improved efficiency along with low-rate solar heat gain co-efficient (SHGC). • For adaptive thermal comfort, 70% households will adopt a setpoint temperature of 28°C by 2070.
	Operational Aspect	Adopting efficient CoPe (considering BEE efficiency standards).
Material	Alternative Materials	The percentage share of alternative construction materials will increase by 2050, exhibiting the transition to low-carbon materials. AAC is assumed to be the predominant material, followed by fly-ash blocks and SEB in the material mix. These materials could significantly reduce cooling energy demand and embodied GHG emissions.
Renewable Energy	RTPV	The installed capacity is projected to reach 552 GW by 2070.
Commercial Sector		
Energy Performance	Green Buildings	Adopting efficient EPI for commercial spaces (considering green buildings norms).

Table 5: Interventions for ILS

Section	Interventions	Description
Cement	Clinker Substitution	Clinker-to-cement ratio has been reduced to 0.50 by 2070.
	Thermal Substitution	Fuel share for cement production has been considered, expecting a 60% share of alternative fuel and a 22% share of hydrogen fuel, with complete phasing out of coal by 2070.
	Electricity-Related	• The share of electricity from grid verses electricity generated from captive power plants is assumed to reach 100% by 2070. • Improvement in efficiency and waste-heat recovery in cement production process.
Steel	Process and Fuel	The share of production is assumed to be 40% via blast furnace – basic oxygen furnace (BF-BOF), 40% via green hydrogen electric arc furnace (EAF), and 20% via scrap steel by 2070.
	Hydrogen in BF-BOF	Use of hydrogen as an auxiliary reducing agent to decrease coke consumption will reach its maximum potential by 2050.
	Electricity-Related	The share of electricity from grid verses electricity generated from captive power plants is assumed to reach 100% by 2070.
Aluminum	Electricity-Related	The share of electricity from grid verses electricity generated from captive power plants is assumed to reach 100% by 2070.
Power	No New Coal	No new coal power plants will be sanctioned after 2025.
	Battery Storage	Storage potential is assumed to be 400 GW by 2050.

Interventions for BLS + ILS

The third decarbonisation scenario aims to optimise outcomes by leveraging interventions from the two scenarios described in Tables 4 and 5 to realise the maximum mitigation potential for the buildings sector.

4 Results and Discussion

The annual GHG emissions trajectory for the five scenarios is presented in Figure 6 and the energy demand is given in Figure 7.

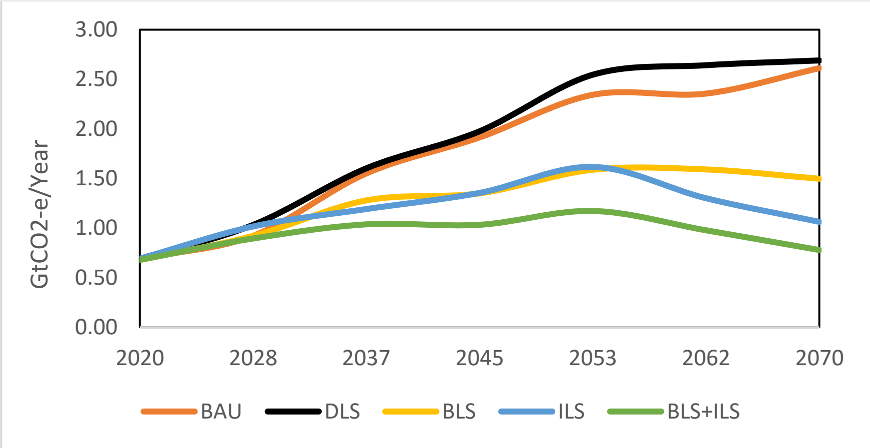


Figure 6: Annual GHG emissions across scenarios

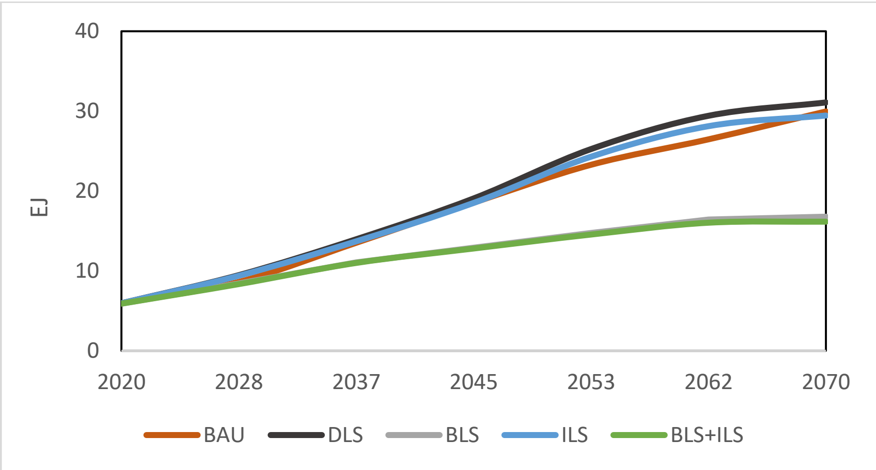


Figure 7: Annual energy demand across scenarios

4.1. BAU Scenario

Emissions from the buildings sector are categorised into direct or Scope 1 emissions (attributable to cooking fuel usage) and indirect or Scope 2 emissions (linked to electricity consumption). Additionally, emissions from the construction sector are included as Scope 3 emissions (Building Innovation Hub, 2023). While efforts to reduce Scope 1 and 2 emissions are progressing, owing to focussed actions in these areas, tackling Scope 3 emissions in the buildings sector remains a challenge due to the complex and diverse supply chain, external factors that are difficult to control directly, and the global nature of production and transportation of construction materials. The contribution of these emissions in the current total GHG emissions from buildings sector is presented in Figure 8. In the BAU scenario, the projected cumulative emissions for India by 2070 stand at 426 $GtCO_{2\text{-}e}$, surpassing the fair share budget of 89.4 $GtCO_{2\text{-}e}$ by 477%, with the cumulative emission from buildings sector alone exceeding the carbon budget by 2% (90.85 $GtCO_{2\text{-}e}$).

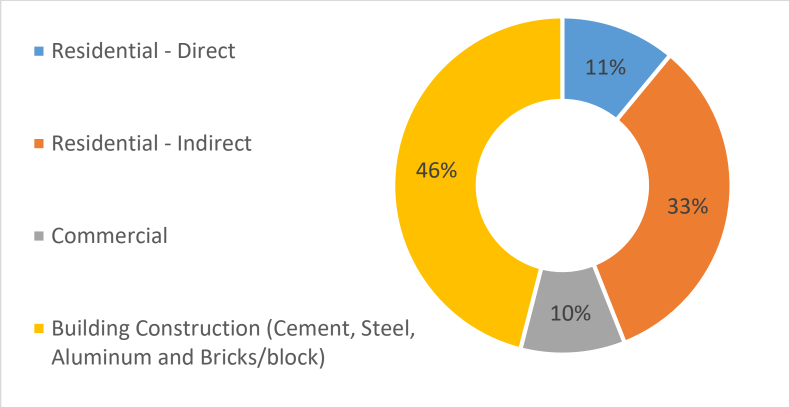


Figure 8: Break-up of GHG emissions contribution from buildings sector (current emissions being 0.77 $GtCO_{2-e}$)

4.2. DLS Scenario

The DLS scenario has the highest energy demand (32.4 EJ) and contributes the most to GHG emissions, owing to an increase in housing stock, and educational and healthcare buildings to cater to the SDGs. Emissions increase due to growing consumption of appliances, cooking fuels, and material construction.

Looking at the broader climate context, in the DLS scenario, the emissions from the buildings sector alone overshoot the national 1.5 °C budget by 8% (97.11 $GtCO_{2-e}$), clearly indicating that this scenario, though catering to developmental goals, is the most unsustainable pathway.

4.3. Decarbonisation Scenario I (BLS)

The interventions in this scenario are buildings-sector-specific and directly inform the energy demand and emission reduction potential of the sector. These interventions are detailed in Table 4.

The maximum emission reduction that the sector achieves in 2070, with respect to the BAU trajectory, is 44%, wherein embodied emissions see a reduction of 16% and operational emissions reduce by 69%. The reason for such large reduction in operational emissions is the predominantly operational nature of interventions. It is to be noted that these interventions are driven by behaviour change in consumers and while optimisable with policy, are difficult to implement. Another challenge is posed by the fact that these interventions cater to different stakeholders across the building life-cycle, making it not only difficult to implement, but also to monitor and ensure collective action that could have multiplicative impacts. Interestingly, under this scenario, the buildings sector emerges a key player, consuming 72% of the carbon budget allocated for 1.5 °C and 33% for 2 °C.

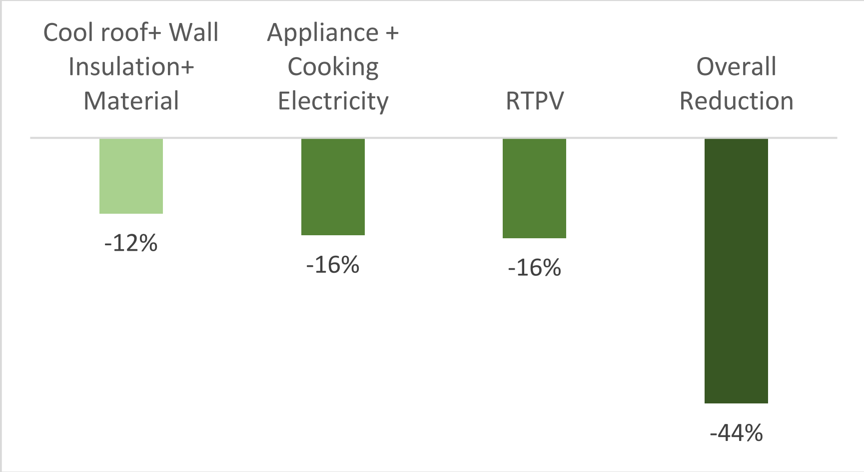


Figure 9: Annual emission reduction potential of different interventions led by buildings sector by 2070[6]

- Passive design aspects, such as material choices and incorporation of wall insulation and cool roof is beneficial for reducing AC consumption per household by improving thermal comfort. They collectively account for a 12% decrease in emissions when compared to the BAU scenario. In the overall trajectory, it has the least emission reduction potential wherein it is observed that renewable and localised power generation takes the bigger chunk. However, they are very cost–effective, and, owing to their direct impact on consumption/usage of ACs, prove to be an important intervention for thermal comfort. In addition, these solutions can aid in alleviating urban-heat-island effect in cities, which has prompted the inception of Telangana's Cool Roof Policy that aims to cover 7.5 m^2 of roofs in 2023–2024 and 300 m^2 area by 2030 (Government of Telangana, 2023).
- A 100% shift to electric cooking in urban areas and a 70% shift in rural areas, alongside the adoption of high-efficiency appliances, leads to a 16% reduction in emission, as compared to the BAU scenario. The mitigation potential can be even higher if AC consumption reduces further. This can happen in two ways: i) keeping thermal comfort in check through implementation of passive solutions; and ii) reducing AC usage—mindful usage at an individual level—as highlighted in the LiFE mission (Niti Aayog, 2023). A 2019 mandate by BEE has suggested that all ACs be sold with a default temperature setting of 24 °C (Hindustan, 2020). A previous guideline by the same organisation suggests that public office buildings use ACs with a default temperature setting of 24 °C-25 °C (Ministry of Power, 2018). This can be extended to residential buildings as well to ensure control over temperature setting. The transition to high-efficiency appliances will incur an initial higher purchase cost. However, factoring in the discount rate, the cumulative cost saving from the transition would be in the range of INR

[6] The reduction potential of individual lever does not reflect the total reduction potential. This is because the levers are not independent—they impact each other; for example, the implementation of passive design aspects reduces the cooling demand, subsequently reducing the need for ACs and electricity consumption. Similarly, the adoption of high-efficiency appliances lessens electricity demand in accordance with the efficiency trajectory of these appliances. When these interventions are implemented together, their collective impact drives the electricity demand for cooling and the associated emissions.

40.01 trillion by 2070, as presented in Table 6 of the Appendix. The CAPEX of appliances will reduce over time as the technology matures, resulting in increased cost savings alongside emission reduction.

- RTPV plays a significant role in emission reduction and can, by itself, bring about 16% reduction in emissions, as compared to BAU. The grid-connected solar rooftop programme of MNRE outlines an ambition of achieving 40,000 MW installed capacity by 2026 from solar rooftop projects (Ministry of New and Renewable Energy, 2015), which will demand an investment of INR 1.54B[7]. If the area for RTPV installation was to increase, a higher mitigation potential would be possible. Therefore, it is important to consider the relationship between sprawl/compact urban form and area available for RTPV, since if high-rises were to increase, the space for solar rooftop will reduce, while the demand for electricity per building would increase, making solar rooftop an unsuitable and expensive technology to implement. Therefore, to encourage solar rooftop systems, it is important to ensure that cities continue to have higher percentage shares of low- and mid-rise apartments, which can justify the purpose of installing solar rooftops in residential and commercial buildings. The flipside would be that such a sprawl-oriented urban form would put pressure on land resources. In addition, solar panels are known to increase surface temperature of the roof, which can add to the heat gain from the roof without proper insulation. However, the integration of green roof with photovoltaic (PV) panels is a promising technology as green roof reduces temperature fluctuations and helps to maintain an efficient microclimate around the PV panels, improving its efficiency (Shafique et al., 2020). The challenge in the case of solar rooftop systems is the high purchase cost, which may make the implementation difficult in residential households. This intervention is also dependent on behavioural changes in consumers and therefore continued schemes are crucial to ensure this lever with a high-mitigation potential can succeed in driving down emissions in the future.

4.4. Decarbonisation Scenario II (ILS)

In this scenario, thoughtful consideration has been given to the combined mitigation potential of the industrial and power sectors, closely intertwined with the buildings sector. The integration of various decarbonisation strategies, as outlined in Table 5, amplifies the effectiveness of the interventions.

The overall reduction in buildings sector emissions (as compared to the BAU scenario) is 59% in 2070. It is crucial to highlight that the current assessment of the energy demand in buildings sector does not incorporate the reduction in energy demand due to these interventions. This is because the sectoral reduction in energy demand within the industrial and power sectors doesn't precisely mirror the energy demand reduction specific to the buildings sector. With the incorporation of supply-side interventions in the power sector (such as no new addition in coal power plants post 2025 and the integration of enhanced battery storage potential), a substantial 84% reduction in operational emissions is observed in 2070, compared to the BAU scenario. Furthermore, there is a notable 32% reduction in embodied emissions. In terms of carbon budget, under this scenario, the buildings sector will

[7] Calculation is based on current benchmark cost with 30% subsidy.

be consuming 70% of the remaining budget set for limiting the global temperature to 1.5 °C and 30% to stay within 2 °C by 2070.

Some of the key observations of the scenario are summarised in Figure 10:

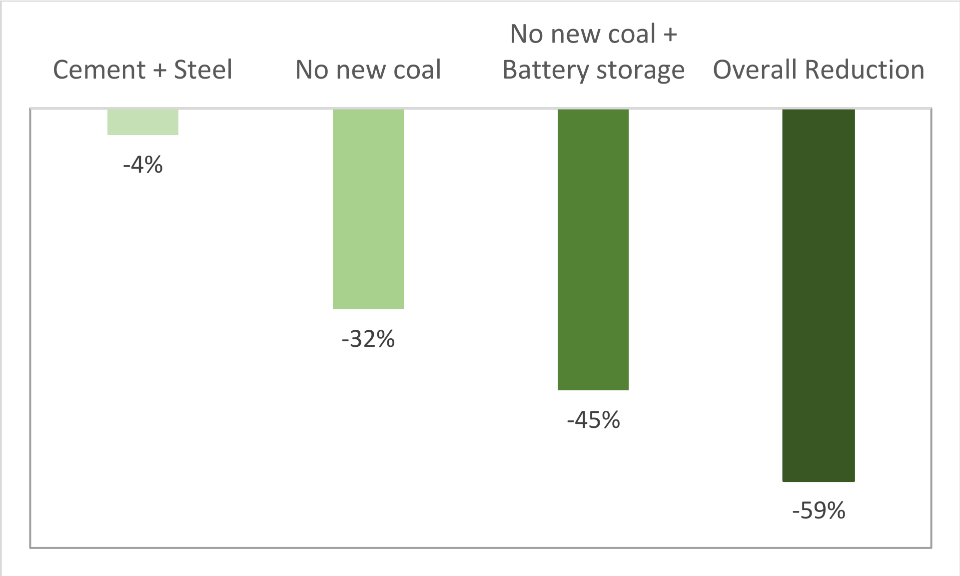


Figure 10 Emission reduction potential of different interventions led by industry sector

- Cement and steel—crucial components for the buildings sector—are expected to experience significant growth in demand to meet the developmental needs of our expanding economy. The production processes for cement and steel are both energy- and emissions-intensive. Despite implementing an array of interventions, the cross-sectoral impact of reducing emissions from the buildings sector is a meagre 4%, as shown in Figure 10. The potential impact on emissions might increase through broader strategies beyond current efforts in cement and steel decarbonisation. However, the Indian cement industry has already achieved the highest level of performance in terms of efficiency and technology, making further emission reductions challenging without substantial investments in carbon capture utilisation and storage (CCUS) technology. In the steel industry, the focus is on the production process, with BF-BOF constituting the dominant share, followed by EAF and induction furnace in India. The National Steel Policy, 2017, projected an increase in the share of BF-BOF by 2035, followed by a phase-out approach by 2070 (Ministry of Steel, 2017). This aligns with our interventions targeting a 40% hydrogen-based production via EAF by 2070. However, achieving 100% steel production through hydrogen-EAF would necessitate an additional 580 GW (+20%) operating capacity in 2070[8] (Ashok et al., 2022), demanding significant electricity-intensive capacity additions in the power sector. Therefore, while addressing emissions in the cement and steel industry remains pivotal, achieving a net-zero pathway for buildings requires comprehensive strategies encompassing the entire buildings sector.

[8] Assuming that electricity is sourced from a low-carbon grid.

- The implementation of supply-side interventions, particularly the 'no new coal' policy, effects a significant reduction of 32% in emissions, primarily operational, in 2070. With this policy in place, emission reduction of 0.84 $GtCO_{2\text{-}e}$ can be achieved. The policy facilitates the gradual phase-out of coal-based power plants, promoting a smoother transition to cleaner energy sources. However, its implementation poses challenges, notably a nearly 50% increase in cumulative costs for the power sector by 2070 (Ashok et al., 2022), mainly from elevated transmission expenses over the period. The other challenges are associated with renewable energy (RE) and include securing land for plant installation and ensuring grid stability. Despite these hurdles, the 'no new coal' policy stands as a pivotal measure in reducing cross-sectoral emissions.
- An additional intervention in the power sector involves an increase in battery storage capacity to store solar power during periods of low demand and use it during peak-load hours. The combined effect of this enhanced battery storage capacity, along with the 'no new coal' policy, results in a notable 45% reduction in emissions by 2070, translating to a substantial saving of 1.17 $GtCO_{2\text{-}e}$. On the downside, increasing battery storage entails challenges such as high costs, the availability of suitable land, resource availability (lithium, cobalt, and nickel), technological limitations, grid-integration complexities, regulatory frameworks, and public perception. Addressing these issues requires a comprehensive approach involving technological innovation, supportive policies, and public engagement.

4.5. Decarbonisation Scenario III (BLS + ILS)

In this scenario, the interventions from the other two scenarios are combined to comprehensively assess the overall mitigation potential of the buildings sector. By integrating strategies from both scenarios, we seek a holistic understanding of the collective impact on mitigating challenges and developing a roadmap for decarbonisation of the buildings sector. This leads to a reduction in emissions by 72% and energy demand by 47% in 2070, resulting in a substantial saving of 1.83 $GtCO_{2\text{-}e}$. Notably, the mitigation potential of the BLS scenario alone accounts for 44%, whereas that in the ILS scenario contributes 59%, highlighting the significant contribution of industrial sector in achieving an overall 72% reduction. As regards the carbon budget, in this scenario the buildings sector is projected to utilise 54% of the remaining allowance earmarked to restrict global temperature increases to 1.5 °C and 24% to adhere to the 2 °C limit by 2070.

4.6. Additional Insights

4.6.1 Thermal comfort vs. appliance-ownership-based cooling demand

Thermal comfort for all through sustainable cooling is an important aspect highlighted in ICAP. In alignment with this, we have analysed two scenarios for estimating the cooling electricity demand, one based on thermal comfort requirement of residential buildings and another dependent on the AC uptake—based on current market trends and usage pattern. According to SAFARI projections, under the BAU scenario, the electricity consumption for meeting space-cooling demand in 2023 is estimated to be 1260 TWh. However, driven by the average number of cooling appliances per household, the annual electricity consumption for cooling reached 276 TWh. This implies that only 22% of the total 'thermal comfort' requirements were fulfilled for the overall population, owing to the low penetration rate of 7-

10% (Thomas, 2023). Anticipating a surge in appliance ownership (69% by 2040 ("AC Penetration in India," 2023)) due to increasing incomes and urbanisation, our projections indicate that electricity demand from cooling appliances is set to surpass 'thermal comfort' needs by 2050 (Figure 11). This presents a substantial opportunity for energy savings, potentially achievable through regulatory shifts incorporating 'thermal comfort' considerations. In terms of emissions reduction, this transition could avoid 64.25 million tCO_{2-e} in 2070. The potential of saving another 440 million tCO_{2-e} through the adoption of passive design aspects is also present.

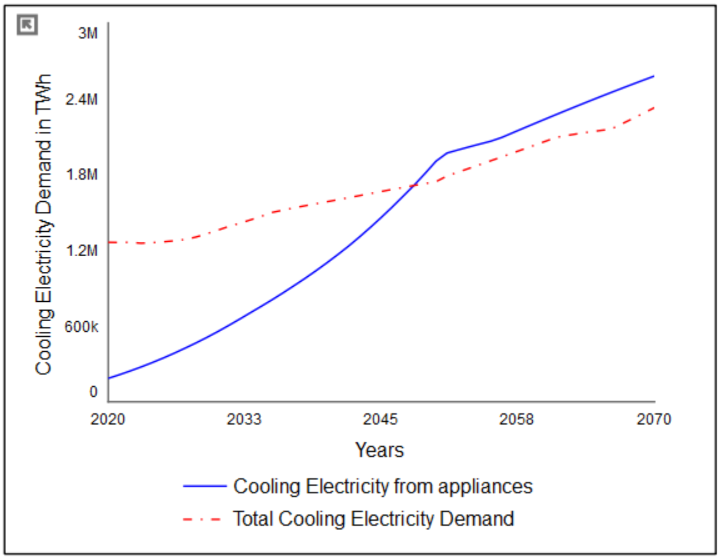


Figure 11 Thermal comfort vs. appliance-ownership-based cooling

4.6.2 Behaviour-driven vs. policy-driven buildings decarbonisation

Buildings sector decarbonisation involves interventions embedded in behavioural changes, such as shifting to a more sustainable cooking fuel, using alternative construction materials, mindful and responsible consumption of appliances, and practising energy conservation in general. Encouraging mindful consumption across households in the country can help achieve significant emission reductions. The same has been stressed upon in Mission LiFE, wherein the theme of 'save energy' has substantial alignment with interventions focused on energy efficiency in buildings. While behavioural changes are challenging in terms of implementation and monitoring, policy can play an enabling role. For instance, when LPG penetration in rural households faced economic challenges, the *Pradhan Mantri Ujjwala Scheme* was launched in 2016 (National Informatics Centre, 2024) to increase the uptake of LPG cooking fuel, which the is not only sustainable, but also safer. However, according to the recently released NSSO report, only 49.4% of rural households use LPG and the rest continue to use other fossil-fuel-based cooking fuels (National Sample Survey Office, 2023). Similarly, mindful usage of ACs, as recommended by BEE, would enable behaviour change in consumers. This underlines the importance of supporting behavioural decarbonisation interventions with policy. While the intended benefits may not be achieved in the given timeframe, such policies can aid behaviour change, which remains a difficult obstacle to overcome.

4.6.3 Net-zero pathways for buildings sector

In the pursuit of net-zero emissions, the initial focus was on a series of comprehensive interventions, resulting in a notable 70% reduction in emissions. Following these interventions, the next step involves embracing circular economy practices within the construction industry. This includes promoting reuse, recycling, and repurposing of materials to minimise waste and environmental impact, representing an additional step in fostering an efficient and sustainable buildings sector. Another vital consideration relates to prioritising renovation over new construction, so that emissions are lowered by avoiding construction of new buildings. This emphasises the importance of sustainable practices throughout the building life-cycle. Continuing this trajectory, the subsequent focus is on addressing the remaining emissions. This necessitates integrating advanced technologies, such as CCUS, in the power and industrial sectors, alongside the adoption of green hydrogen for steel manufacturing. However, it is crucial to acknowledge the considerable financial implications and associated negative impacts linked to these advancements. Challenges include navigating the high costs of implementing CCUS and green hydrogen technologies, ensuring a consistent and sustainable supply of resources for these advancements, addressing potential environmental and social impacts, and fostering widespread industry adoption despite the existing infrastructural and regulatory hurdles. Such multifaceted challenges call for a comprehensive and balanced approach to achieving net-zero emissions in the buildings sector.

5 Conclusion

This report has put forth an integrated model for India's buildings sector—within the larger framework of SAFARI—addressing issues of development, energy, resources, and climate comprehensively. The driving forces in SAFARI's buildings sector model are India’s development goals and socioeconomic factors such as population and GDP. Notably, the development goals encompass housing, healthcare, education, and thermal comfort, as detailed in our earlier reports (CSTEP, 2018, 2020). SAFARI provides the flexibility to adjust over 100 intervention levers, impacting energy, emissions, and resource footprints. Utilising this framework, we have developed five scenarios: a BAU scenario that follows current practises and trends; a DLS scenario that focusses on meeting the development and living standards goals; and three decarbonisation scenarios driven respectively by buildings initiatives, industry initiatives, and comprehensive initiatives (buildings plus industry). These scenarios serve as illustrative examples in our efforts towards achieving net-zero emissions in India's buildings sector. In the BAU scenario, which envisions current practices persisting until 2070, emissions are projected to reach 2.61 $GtCO_{2\text{-}e}$, resulting in a high-emission trajectory with no consideration for developmental targets. The DLS scenario places a significant emphasis on achieving developmental objectives while ensuring considerable living standards. However, in this approach, there is a lack of consideration for climate impacts. Consequently, the emission trajectory in the DLS scenario is expected to surpass that of the BAU scenario, reaching 2.69 $GtCO_{2\text{-}e}$ in 2070. This heightened trajectory is attributed to the increased demand for providing adequate infrastructure and ensuring comfortable living conditions. The remaining three scenarios concentrate on achieving a harmonious balance between developmental aspirations and climate impact mitigation. In the BLS context, the emphasis is on interventions that directly influence the buildings sector. Many of these interventions are economically feasible, particularly those related to building design, including passive solutions like cool roofs, wall insulation, and enhancements in the SHGC through vernacular design and WWR optimisation. Within the higher-cost spectrum, strategic measures include transitioning to energy-efficient appliances and integrating RTPV. Despite their relatively higher costs, these interventions have proven effective in managing the trajectory of emissions, ultimately helping to cap it at 1.5 $GtCO_{2\text{-}e}$. In the ILS scenario, the emphasis is on addressing buildings sector emissions by intervening in the related industries and the power sector. The proposed interventions, while requiring significant financial commitments, hold the potential to bring about transformative improvements. These include making production-process-related changes in industry, harnessing waste heat for energy recovery, and steering towards a more sustainable energy mix in the power sector. It is important to note that in this scenario the projected emissions for 2070 amount to 1.06 $GtCO_{2\text{-}e}$. This highlights the scenario's potential to significantly reduce emissions in the buildings sector, while simultaneously driving industry advancements and power sector sustainability.

The third decarbonisation scenario capitalises on the previous scenarios to unlock the full mitigation potential of the buildings sector. By building upon the interventions outlined earlier, this scenario aims to achieve a substantial reduction in emissions, ultimately reaching 0.78 $GtCO_{2\text{-}e}$ in 2070. This outcome reflects the ambitious yet achievable goal of significantly mitigating carbon emissions from the buildings sector through a comprehensive and coordinated approach. The key interventions with significant mitigation potential include:

- Restriction on approving the construction of new coal-fired power plants.
- Integration of RTPV within residential spaces.
- Transitioning to efficient appliances and uptake of electric cooking in both urban and rural households.

While our BLS+ILS scenario has commendably led to a 72% reduction in emissions, the journey to attain net zero requires focussed efforts for achieving net zero in both power and industrial sectors. Investing in CCUS technology is essential for reducing further emissions, despite the challenges it poses. However, policy and regulations must explicitly outline that CCUS should serve as a last-resort technology in progressing towards net zero, emphasising the importance of prioritising cleaner and more sustainable alternatives.

6 Way Forward

Though this study provides a model for pursuing the competing priorities of development and climate change mitigation, creating a roadmap for attaining net-zero emissions in the buildings sector necessitates a still more comprehensive analysis, particularly in the development of scenarios.

Our next steps will thus focus on scrutinising diverse scenario narratives and exploring the following aspects to supplement the net-zero roadmap for the buildings sector in India:

- **Urban-form and land-use integration:** SAFARI currently includes distinct types of building densities, depending on varying FSI scenarios. Ultimately, these represent a sprawl, mixed, or compact building urban form. The linkage between urban form and land area can be explored through the lens of FSI. This allows us to model the impact of different urban patterns to capture their effects on land use and land cover. A sprawl scenario, coupled with a steadily growing population, would require an immense amount of land, whereas a compact scenario would reduce pressure on land. Another factor to consider, especially in the sprawl scenario, is competition for land from RE, forests, and transport sectors, making land an interesting resource to explore in terms of resource allocation (based on sectors). The competition for land is becoming a crucial topic amidst a noticeable policy push for RE generation. Additionally, the impact of urban form has implications on interventions like AC consumption (driven by thermal comfort considerations of the building) and RTPV adoption (due to roof area availability). Another area of interest is the nexus between green cover and temperature—which can also be interpreted through urban form — and subsequently its connection with cooling energy demand. Building materials and green area within cities are dominating factors in the context of urban-heat-island effect, which can further drive up AC consumption. Therefore, understanding the relationship among urban form, buildings materials, and urban heat islands is instrumental for reducing AC consumption and usage.
- **Construction Material Technology:** Currently, SAFARI includes block construction method and Mivan technology to determine embodied emissions from materials and thermal transmittance of walls within the model. However, integrating other alternative and upcoming material construction technologies and accounting for their embodied and operational emissions are crucial to assess which technology would aid in emission reduction without compromising on the speed of construction.
- **Electric Vehicle (EV) impact on buildings sector electricity**: According to the 2023 Economic Survey, India's domestic EV market will see a 49% compound annual growth rate between 2022 and 2030, resulting in 10 million vehicles on the roads by 2030 (Singh, 2023). As the push for transport electrification continues, it is crucial to comprehend the potential impact of EV charging on the power grid, as well as that of increased electricity demand from both residential and non-residential buildings. The Union Ministry of Housing and Urban Affairs, in 2019, amended the Model Building Bye-Laws, 2016, and suggested that at least 20% of parking spots in new buildings be equipped with EV-charging infrastructure (Ministry of Urban Development, 2016). While these amendments are yet to be adopted by many states, further research

should include the impact of this amendment on residential and non-residential buildings. With the increased penetration of EVs, understanding the potential impact of EV charging (on the power grid) is vital, given that it will escalate the electricity demand in residential and commercial buildings.

- **Performance EPI:** SAFARI currently considers the EPI benchmark for different commercial buildings as per the BEE. In order to minimise the energy demand, a set of green EPI values are introduced with variation in the percentage of green building in each sector, based on various case studies. Since there is a lack of experimental studies on benchmarking the EPI values for commercial buildings in India, developing EPI benchmarks for a comprehensive set of commercial buildings is essential. Future research should take into consideration the savings in energy consumption resulting from star labelling of buildings, besides conducting other benchmarking studies in India to optimise the EPI benchmark on the basis of the performance of a building over the years.

7 References

AC Penetration in India: Households with AC in India. (2023). RationalStat. https://rationalstat.com/ac-penetration-india-households/

Ashok, K., Kumar, P., Natarajan, R., & Srinivasan, S. (2021). *Energy and Emissions Implications for a Desired Quality of Life in India via SAFARI*. https://cstep.in/drupal/sites/default/files/2021-07/CSTEP_SAFARI_Final_Report_July2021.pdf

Ashok, K., Ravishankar, K., & Natarajan, R. (2022). No silver bullet: Essays on India’s net-zero transition. https://cstep.in/publications-details.php?id=2229

Building Innovation Hub. *(2023). Understanding Building Emissions*. Building Innovation Hub. https://buildinginnovationhub.org/resource/get-started/understanding-building-emissions/

Bureau of Energy Efficiency (BEE). (2018). *Eco-Niwas samhita, Part I: Building envelope*. https://beeindia.gov.in/sites/default/files/ECBC_BOOK_Web.pdf

Climate equity monitor*. (2024). GHG Emissions*. https://climateequitymonitor.in/#ghgEmission

Das, P. (2022). *Unlocking the Full Potential of Rooftop PV In India Using Consumer Adoption Modeling*. https://www.nrel.gov/docs/fy22osti/80751.pdf

de la Rue du Can, S., Khandekar, A., Abhyankar, N., Phadke, A., Khanna, N. Z., Fridley, D., & Zhou, N. (2019). Modeling India’s energy future using a bottom-up approach. *Applied Energy*, *238*, 1108–1125. https://doi.org/10.1016/j.apenergy.2019.01.065

Dellink, R., Chateau, J., Lanzi, E., & Magne, B. (2017). *Long-term economic growth projections in the Shared Socioeconomic Pathways*. Global Environmental Change. Global Environmental Change, 42, 200-214. https://www.sciencedirect.com/science/article/pii/S0959378015000837

Government of Telangana. *(2023). Telangana Cool Roof Policy 2023—2028*. https://www.nrdc.org/sites/default/files/2023-04/telengana-cool-roof-policy-booklet.pdf

Hindustan, T. (2020, January 18). HT Tech. https://tech.hindustantimes.com/tech/news/govt-has-mandated-24-degrees-as-the-default-temperature-for-acs-what-does-this-mean-and-how-will-it-affect-you-story-Zdt1BZOlkBMgmnlEmloc2J.html

India—Housing Condition Survey: NSS 65th Round. (2016). National Sample Survey Office - M/o Statistics and Programme Implementation (MOSPI), Government of India (GOI). http://www.icssrdataservice.in/datarepository/index.php/catalog/85/related_materials

International Organization for Standardization (ISO). (2006). ISO 14044:2006—Environmental management—Life cycle assessment—Requirements and guidelines. https://webstore.ansi.org/standards/iso/iso140442006

IPCC. (2022). IPCC AR 6 Report. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Kumar, P., Natarajan, R., & Ashok, K. (2021). Sustainable alternative futures for urban India: The resource, energy, and emissions implications of urban form scenarios. Environmental Research: Infrastructure and Sustainability, 1(1), 011004. https://doi.org/10.1088/2634-4505/ac048e

Kumar, S., Kumar, N., Cherail, K., Setty, S., Yadav, N., Goenka, A. (2017). Transforming the Energy Services Sector in India: Towards a Billion Dollar ESCO Market. *Alliance for an Energy Efficient Economy*. https://aeee.in/our_publications/transforming-the-energy-services-sector-in-india-towards-a-billion-dollar-esco-market/

Maithel, S., Chandiwala, S., Bhanware, P., Rawal, R., Kumar, S., Gupta, V., & Jain, M. (2020). Developing cost-effective and low-carbon options to meet India’s space cooling demand in urban residential buildings through 2050 (India Energy Transformation Platform). http://ietp.in/wp-content/uploads/2020/04/Greentech_Jul2020.pdf

Mani, S., Agrawal, S., Jain, A., & Ganesan, K. (2021). State of Clean Cooking Energy Access in India. Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/ires-report-on-state-of-clean-cooking-energy-access-in-india.pdf

Ministry of Housing & Urban Poverty Alleviation. (2017). Pradhan Mantri Awas Yojana (Urban) – Housing for All, Credit Linked Subsidy Scheme for Middle Income Group (CLSS for MIG) [Operational Guidelines]. https://mohua.gov.in/upload/uploadfiles/files/4CLSS-MIG-Guidelines.pdf Check

Ministry of Housing and Urban Poverty Alleviation. (2013). Affordable Housing in Partnership: Scheme Guidelines. https://mohua.gov.in/upload/uploadfiles/files/7AHP-Guidelines.pdf

Ministry of New and Renewable Energy. (2015). Grid Connected Solar Rooftop Programme. https://mnre.gov.in/grid-connected-solar-rooftop-programme/

Ministry of Power. (2018). Energy Conservation in Building Space Cooling through Optimum Temperature Setting. https://www.mca.gov.in/Ministry/pdf/AcTempNotice_21082018.pdf

Ministry of Steel. (2017). National Steel Policy(NSP), 2017 | Ministry of Steel | GoI. https://steel.gov.in/national-steel-policy-nsp-2017

Ministry of Urban Development. (2016). Model Building Bye-Laws. http://tcpo.gov.in/sites/default/files/TCPO/schemes/MODEL-BUILDING-BYE-LAWS-2016.pdf

National Buildings Organisation, Ministry of Housing and Urban Poverty Alleviation. (2013). State of Housing in India: A statistical Compendum.

National Informatics Centre. (2024). PM *Ujjwala Yojana – Transforming India*. https://transformingindia.mygov.in/scheme/ujjwala/

National Sample Survey Office. (2023). Multiple Indicator Survey in India. https://mospi.gov.in/sites/default/files/publication_reports/MultipleIndicatorSurveyinIndiaf.pdf

Ninjal M Parekh, Bhupendra M Marvadi, & Umang Pate. (2022). *Comparative Studies of Construction Techniques (Conventional Technique Vs Aluminium Formwork Techniques) https://www.ejournal.aessangli.in/ASEEJournals/CIVIL54.pdf*

NITI Aayog. (2015). India Energy Security Scenarios.

Niti Aayog. (2023). LiFE - Lifestyle for Environment. https://www.niti.gov.in/sites/default/files/2023-02/Brochure-10-pages-op-2-print-file-20102022.pdf Document

PTI. (2022). India's urban population to stand at 675 million in 2035, behind China's 1 billion: U.N. The Hindu. https://www.thehindu.com/news/national/indias-urban-population-to-stand-at-675-million-in-2035-behind-chinas-1-billion-un/article65584707.ece

Ramchandra, T. V. (2011). *Hotspots of solar potential in India*. *3178–3186 https://wgbis.ces.iisc.ac.in/energy/paper/hotspots_solar_potential/RSER_hotspots.pdf*

Reddy, B. V. V., & Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. Energy and Buildings, 35(2), 129–137. https://doi.org/10.1016/S0378-7788(01)00141-4

Report of the Technical Group on Urban Housing Shortage (TG-12). (2011). Ministry of Housing & Urban Poverty Alleviation. http://nbo.nic.in/pdf/urban-housing-shortage.pdf

*Sabapathy, A., & Maithel, S. (2013). A Multi-Criteria Decision Analysis based assessment o*f walling materials in India. *Building and Environment*, *64*, 107–117. https://doi.org/10.1016/j.buildenv.2013.02.016

Sarraf, S., Anand, S., Shukla, Y., Mathew, P., Singh, R., Schneider Electric, & Wipro EcoEnergy. (2014). *Building Energy Benchmarking in India: An Action Plan for Advancing the State-of-the-Art~~.~~* https://doi.org/10.2172/1171348

Schwab, K., & Zahidi, S. (2020). Global Competitiveness Report 2020. World Economic Forum. https://www.weforum.org/publications/the-global-competitiveness-report-2020/

Shafique, M., Luo, X., & Zuo, J. (2020). Photovoltaic—Green roofs: A review of enefits, limitations, and trends. 485-497,https://www.sciencedirect.com/science/article/abs/pii/S0038092X20302280

Singh, A. (2023). India's EV Economy: The Future of Automotive Transportation. https://www.investindia.gov.in/team-india-blogs/indias-ev-economy-future-automotive-transportation

Singh, R., Sawhney, R. L., & Bansal, D. (2014). Effect of construction materials on embodied energy and cost of buildings—A case study of residential houses in India up to 60m2 of plinth area. *Energy and Buildings*, *69*, 260–266. h*ttps://doi.org/10.1016/j.enbuild.2013.11.006*

Svarc, J. (2023). Most efficient solar panels 2023. Clean Energy Reviews https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

Syam, A. S., & Sebastian, A. W. (2018). *Quantification and Analysis of Embodied Energy in High-rise RCC Building: A Case Study*. 5(7 453-457). https://krishisanskriti.org/vol_image/30Oct201809105706%20%20%20%20Akhil%20S%20Syam%20%20%20%20%20%20%20%20%20%20453-457.pdf

Thomas, K. S. (2023). *Cooling market heating up: AC sales in India to hit one crore units mark in coming months*. The Week. https://www.theweek.in/news/biz-tech/2023/04/05/cooling-market-heating-up-ac-sales-in-india-to-hit-one-crore-units-mark-in-coming-months.html

UN-DESA. (2019). *World Population Prospects 2019: Highlights*. United Nation. https://population.un.o*rg/wpp/Publications/Files/wpp2019_10KeyFindings.pdf*

UNDP-GEF-BEE. (2020). BEE Energy benchmarks for Commercial Buildings. https://www.beeindia.gov.in/sites/default/files/Flyer_22nd%20Jan.pdf

Weitzman, M. (1998). Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate. https://scholar.harvard.edu/files/weitzman/files/why_far-distant_future.pdf

8 Appendix

i. Urban-heat-island effect and its impact on cooling demand

Given the increasing concern about rising temperatures, the urban-heat-island (UHI) effect is an added risk. The UHI phenomenon develops in cities with a high concentration of heat-absorbing buildings materials and a reduction in vegetation cover due to anthropogenic activities. The temperature hike in an urban area (as compared to the surrounding rural areas) indicates the UHI intensity of the area. Since multiple factors influence the UHI intensity of a city, understanding the underlying mechanisms is crucial for developing appropriate mitigation strategies.

Integrating UHI into a national-level model poses several challenges due to its spatiotemporal characteristics. Many parameters have been considered to capture the effect of UHI and correlate it with the urban form and cooling demand in India. Rescaling UHI on the basis of literature reviews of localised studies is a major roadblock, as granularity is lost in the process of averaging out. While attempts have been made to incorporate the UHI impact on cooling demand, a definitive methodology could not be established, given the microclimatic effects of the phenomenon, which resist generalisation on a global scale.

The subsequent section details the method employed to introduce the UHI effect in the SAFARI model.

Detailed Methodology: The methodology employed to integrate the UHI impact on cooling demand involves utilising land surface temperature (LST) and the Normalized Difference Vegetation Index (NDVI) as key parameters for two major cities—Delhi (composite) and Mumbai (warm-humid)—representing two different climate zones. The temperature data for 12 years (2010–2022) is generated using MODIS[9] and mapped to 17 local climate zones and land use/cover, distinguishing between built types (compact, standard, sprawl) and non-built types (vegetation, water cover, barren surface).

Built types are linked to FSI scenarios, connecting them with the urban form module in the model. The UHI intensity for each zone is calculated by determining the difference in LST between the respective zone and a densely vegetated reference zone. The average UHI intensity for the three built types is calculated and a linear regression analysis is performed considering the average vegetation proportion for each zone, exploring the influence of vegetation on the UHI effect.

Subsequently, a regression analysis is done between the LST of UHI hotspots and the cooling demand from the model, utilising a polynomial curve identified through a literature review. This curve is then applied to determine the cooling demand for non-UHI hotspots.

The difference in the cooling demands corresponding to LST under UHI and under non-UHI impacts is considered as the net impact of UHI on cooling demand. Despite employing this approach, a robust correlation was not achieved, highlighting the complexity of capturing UHI effects on cooling demand in the model.

[9] Moderate Resolution Imaging Spectroradiometer (MODIS) is a satellite-based sensor used for earth and climate measurements.

The use of statistical techniques such as multiple linear regression or random forest regression for analysing data offers scope for bridging this gap. The potential of machine learning and geographic information system can also be explored to better understand the trends and key parameters to be considered for UHI integration.

ii. Transition to high-efficiency appliances: Cost estimation

The CAPEX and OPEX cost estimation of high-efficiency appliances has been described in the methodology section of this report. The cumulative cost savings resulting from this transition by 2070 (in the form of net present value) are presented below.

Table 6: Cost savings due to transition to high-efficiency appliances

Cost in INR trillion	Net present value of low-efficiency appliances	Net present value of high-efficiency appliances
Cumulative cost till 2040	167.77	169.16
Discounted cost till 2040 @ 3%	92.89	93.66
Cumulative cost (2040 – 2070)	540.95	467.09
Discounted cost (2040 – 2070) @ 2%	298.64	257.87
Total discounted cost	391.53	351.53
Savings	40.01	

iii. Tables for methodology section

The built-up area assumptions for each housing category in the model are based on the data given by Ministry of Housing and Urban Poverty Alleviation, and statistical methods like linear interpolation are used to generate the values for the intermediate years (the values for 2070 are assumed, as shown in the Table 7). The housing categories include EWS-LIG (Ministry of Housing and Urban Poverty Alleviation, 2013), MIG-HIG (Ministry of Housing & Urban Poverty Alleviation, 2017) and rural (CRISL, 2018).

Table 7: Built-Up Area Assumptions

Housing category	Built-up area per house (m^2)	
	2011	2070
Urban (EWS–LIG)	30	80
Urban (MIG–HIG)	100	180
Rural	60 across all years	

The model generates the total embodied energy and emissions based on the building blocks and materials used in the residential and commercial buildings sectors. The embodied energy and emissions per m^2 of plinth area (Sabapathy & Maithel, 2013; Singh et al., 2014) for structural blocks and (Reddy & Jagadish, 2003) for materials are given in Table 8.

Table 8: Embodied Energies and Emissions of Materials Used

Material/structural block	Embodied energy (MJ/m² of plinth area)	Embodied emissions (g/ m² of plinth area)
Burnt-clay bricks (BCB)	1499	96045
Stabilised earth blocks (SEB)	655	55458
Fly-ash blocks	569	36109
Fly-ash-lime-gypsum blocks (FaLG)	594	108015
Autoclaved aerated concrete blocks (AAC)	494	66244
Solid concrete block (SC)	782	66872
Hollow concrete blocks	472	66999
Cement	5850	-
Steel	42000	-
Sand	105	-
Aggregate	175	-

Similarly, alternative construction technologies like Mivan shuttering uses materials like RMC, aluminium, steel, and cement. The average demand per m² of plinth area (Ninjal M Parekh et al., 2022; Syam & Sebastian, 2018) of these materials is shown in Table 9.

Table 9: Material Requirement for Alternative Construction Technologies

Material	Average Demand (tonnes/ m² of plinth area)
Cement	0.01038
Steel	0.1013
Aluminum	0.0075
Ready Mix Concrete	1.031

The model assumes four different efficiency trajectories— A, B, C and D— with low, medium, and high efficiency for each of these trajectories. The values employed for these efficiencies for 2011, 2022, 2047, and 2070 are given in Table 10 (assumed to be based on IESS)

Table 10: Appliance-Efficiency Trajectories

Year	Efficiency A			Efficiency B			Efficiency C			Efficiency D		
	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

The built-up area of different types of commercial buildings – hospitality, (FHRAI India Hotel Industry Survey, 2022), office (MOUHA, 2020)(Sandilya, 2016), retail (Patil & Sawant, 2022) and others are assumed on the basis of calculations and discussion with experts. The EPI values are based on the BEE benchmarks (UNDP-GEF-BEE, 2020), and the GRIHA benchmarks (GRIHA, 2019), as shown in Table 11.

Table 11: Commercial Built-Up Area Assumptions for Average Area & Average EPI Values

Type of Buildings	Category	Average Area(m2)	EPI (KWh/m2/year)
Hospitality	Below 3 stars	50	150
	Above 3 stars	80	275
	Others	40	130
Office	Public offices	15	85
	Private offices	10	100
	Others	12	80
Retail	Unorganised	25	45
	Organised	230	55
	Hypermarts	3717	265
Airports	International	50000	320
	Domestic	10000	300
Railways	Suburban	15000	50
	Non-Suburban	50000	120
	Halts	5000	20
Metro	Station	8000	100

iv. Model Calibration

The results generated by the SAFARI model were compared with the values reported by other studies.

The housing stock, on the basis of its structural condition, is classified as good, satisfactory, and bad. The data on housing stock is validated using the data from NSSO report (Ministry of Statistics & Programme Implementation, 2018), as shown in Table 12.

Table 12: Percentage of Housing Stock (Based on Condition of the Structure)

Source	Year	Rural			Urban		
Condition of structure		Good	Satisfactory	Bad	Good	Satisfactory	Bad
SAFARI (Stock)	2018	49550000	76710000	21703000	41059800	28202900	5204020
SAFARI	2018	33.49 %	51.84 %	14.67 %	55.14 %	37.87 %	6.99 %
NSSO Report (584)	2018	34.7 %	50.4 %	14.9 %	58.2 %	35 %	6.9 %

The total residential and commercial built-up area under SAFARI is matched with the values given by IESS 2047 (NITI Aayog, 2015) and AEEE (AEEE, 2018), as shown in Table 13 and 14 respectively. Commercial buildings such as those under hospitality, offices, retail, education, and healthcare are considered for comparing the built-up area.

Table 13 Residential Built-Up Area

Source	Unit	2012	2017	2020	2022
IESS 2047	Billion m^2	-	-	12.4	12.97
AEEE	Billion m^2	-	15.34	-	-
SAFARI	Billion m^2	14.1	15.7	17.1	18.4

Table 14: Commercial Built-Up Area

Source	Unit	2017
IESS2047	Million m^2	898
AEEE	Million m^2	1322.8
SAFARI	Million m^2	1208

The stock of fridge, TV, AC, and fan are covered under appliances stock. These values in SAFARI model are validated with the data from NFHS-5 (National Family Health Survey (NFHS - 5), 2019), ICED (India's Energy Mix & Power Sector Overview, n.d.), IESS (NITI Aayog, 2015), IRS (India Readership Survey, n.d.), BI (BARC India, 2023), IEA (IEA, 2022), RMI (Sachar et al., 2018), and PIER (Sreenivas et al., 2021), as shown in Table 15.

Table 15: Appliance Stock

FRIDGE (in million)									
Data Source	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2021**	**2022**
SAFARI	50.8	57.2	-	87.1	95.3	-	113	131	140
NFHS - 5	-	-	-	-	-	-	114	-	-
ICED	-	-	-	85	-	-	-	-	-
IESS	-	52	-	-	92	-	-	-	143
TV (in million)									
Data Source	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2021**	**2022**
SAFARI	119	126	134	160	169	179	189	-	220
NFHS - 5	-	-	-	-	-	-	203	-	-
IRS	-	-	153	-	-	-	-	-	-
BI	-	-	-	188	-	-	-	-	-
ICED	-	-	-	191	-	-	-	-	-
IESS	-	121.7	-	-	178	-	-	-	250
AIR CONDITIONER (in million)									
Data Source	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2021**	**2022**
SAFARI	15.9	20.2	24.8	39.3	44.3	49.5	54.8	70.6	81.6
IEA	17	18	20	27	30	36	42	57	67
RMI	-	-	-	20.1	23.5	27.4	31.9	43.5	50.8
FAN (in million)									
Data Source	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2021**	**2022**
SAFARI	353	364	-	-	438	-	471	514	543
IESS	-	336	-	-	443	-	-	-	571
PIER	-	-	-	-	-	-	-	542	-

The annual electricity demand from residential buildings in SAFARI is matched with that of Praayas (Sreenivas et al., 2021), IESS (NITI Aayog, 2015), TERI (Spencer & Awasthi, n.d.), GBPN (Rawal & Shukla, 2014), CEA (Ministry of Power, n.d.), as shown in Table 16.

Table 16: Residential Electricity Demand

Source	Unit	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Praayas	TWh	-	-	-	-	-	-	-	-	-	-	325	-
IESS	TWh	-	-	-	-	-	-	-	-	-	299	-	349
TERI	TWh	-	-	-	-	239	-	-	-	-	-	-	-
GBPN	TWh	-	170	-	-	210	-	-	-	-	300	-	-
CEA	TWh	-	183	199	217	-	-	273	288	308	330	-	-
SAFARI	TWh	144	160	179	198	218	238	258	280	303	325	312	346

The cooling electricity demand from the residential buildings in the urban is calibrated using the data from GBPN (Rawal & Shukla, 2014), LBNL (de la Rue du Can et al., 2019), AEEE (AEEE, n.d.), and IETP (Maithel et al., 2020), as given in Table 17.

Table 17: Residential Cooling Electricity Demand

Cooling Electricity Demand (TWh)	**Methodology**	**2015**	**2017**	**2020**
Urban				
SAFARI	Buildings envelope + Technology	313	351	414
GBPN	Urban AC- and Urban envelope-related energy demand	-	-	-
LBNL	Appliance-based technology	125	-	-
AEEE	Appliance-Based Technology	-	126	-
IETP	Buildings envelope+ technology	-	-	326
SAFARI (Urban+Rural)		1130	1180	1260

The total electricity demand generated for commercial buildings in SAFARI is compared with CEA (Ministry of Power, n.d.) data, as shown in Table 18.

Table 18: Commercial Electricity Demand

Source	Unit	2013	2014	2015	2018	2019	2020	2021
SAFARI	TWh	71.3	74.4	77.4	86.4	90.0	93.8	98.7
CEA	TWh	72.7	74.2	78.3	93.7	98.2	106.0	86.9

CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Bengaluru
No.18, 10th Cross, Mayura Street, Papanna Layout,
Nagashettyhalli (RMV II Stage), Bengaluru-560094
Karnataka, India

Noida
1st Floor, Tower-A, Smartworks Corporate Park, Sector-125,
Noida-201303, Uttar Pradesh, India

www.cstep.in | +91-8066902500 | cpe@cstep.in | @cstep_India