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Build Right the First Time

Scaling Adoption of Net-Zero Carbon Buildings in India



Report / February 2025

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Climate Centre for Cities

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Disclaimer: The data and analyses presented in this report are based on currently available information and are intended to provide projections rather than predictions of future outcomes. These projections are subject to change as new data and insights become available. The findings should be interpreted cautiously and used as a guide for planning and decision-making rather than a definitive forecast.

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Table of Contents

Authors and Acknowledgements 3

Executive Summary 5

Introduction 8

Role of India's Building Sector in India's Climate Goals 9

Defining the term "Net-Zero Carbon Building" 13

Need for Standardising the definition of a "Net-Zero Carbon Building" 14

Implementing Net-Zero Carbon Buildings in India 16

Proposed Definition of "Net-Zero Carbon Building" 16

Scope and Applicability of the "Net-Zero Carbon Building" Definition 17

Roles of Key Stakeholders in Net-Zero Building Implementation 18

Quantifying the Savings and Cost of Recommended High-Impact Building Decarbonisation Measures . 19

Recommended High-Impact Decarbonisation Measures for India's Buildings Sector 21

Proposed Behavioural Change Intervention Framework 34

Barriers to Adoption of Energy-Efficient Behaviours. 35

Recommendations for Targeting Change in Consumer Behaviour and Choices 35

Roadmap to Mainstream Net-Zero Carbon Buildings 38

Comprehensive Policy Recommendations to Enhance Adoption within India's Built Environment 43

Scaling Up Cool Roofs in the Country 43

Increasing Penetration of Energy-Efficient Fans in India's Residential Sector 45

Increasing Penetration of Super-Efficient ACs in India's Residential Sector 45

Cement and Concrete Decarbonisation 46

Steel Decarbonisation 48

Appendices 51

Appendix A: Defining a Net-Zero Carbon Building 51

Appendix B: Modeling Assumption 53

Endnotes 55

Executive Summary

India's economy is experiencing robust growth, with its building stock expanding proportionately. It is estimated that India will more than double its floor area by 2050, and its associated carbon emissions will almost quadruple. According to an analysis done by RMI and the National Institute of Urban Affairs (NIUA) in 2020, India's building construction sector accounts for a third of India's energy consumption, while an additional 10% of the national energy consumption can be attributed to the manufacture of building materials and construction activities.[1] In a previously published report, a whole-system approach for India's building construction sector was recommended to maximise its contribution towards achieving India's ambitious Nationally Determined Contribution (NDC) 2030 climate goals. In this report, we build on the foundational work done in *From the Ground Up* report by standardising the definition of net-zero carbon buildings in India, delve into interventions to decarbonise the sector, and propose associated pathways for its implementation at the national and sub-national level.[2,i]

Due to rapid urbanisation, India's urban population is projected to be 612 million in 2030 and 843 million by 2050 due to natural growth, urban migration, and recategorisation.[3] This creates a need for housing to accommodate this increase in population.[4] The timing of this development presents India with a unique opportunity to build right the first time. The building sector will play an important role in India meeting its ambitious carbon reduction goals announced at COP26 — reducing carbon intensity by 45% by 2030 (compared to 2005 levels) or creating an additional carbon sink of 2.5 to 3 gigatonnes (Gt) of CO_2 emissions through forest and tree cover by 2030 and ultimately achieving net zero by 2070.[5] This report proposes the adoption of five high-impact decarbonisation measures as a pathway to mainstream net-zero carbon buildings in India's building sector. The interventions in this report prioritise emissions from space and embodied carbon from steel and cement use in the building sector. The analysis in this report aims to provide a data-based assessment of the potential benefits of high-impact decarbonisation measures relying on the best available information. By offering these insights, the report hopes to guide the strategic implementation of decarbonisation strategies across India's growing building sector.

The five high-impact interventions identified in this report, when integrated with the decarbonisation of the electric grid, present a feasible pathway to achieving decarbonisation of India's built environment. By 2050, annual emissions are projected to be just one-fifth of the business-as-usual scenario.[ii]

The five interventions:

- Adopting **cool roofs** in new building construction, assuming a phased adoption over time, has the potential to lower operational carbon emissions from the building sector by **4%**.
- Replacing traditional fans with new **5-star fans** in new construction projects has the potential to lower the Indian building sector's operational carbon emissions by **3%**.

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i This report uses a subset of data that was used for the *From the Ground Up* report published in collaboration with NIUA. The grid emission factors to calculate the greenhouse gas (GHG) emissions have been updated in the current analysis to reflect latest trends of grid decarbonisation in India.

ii We present numbers in this report both annually and cumulatively because this dual approach provides a comprehensive view of progress and highlights the significance of sustained efforts in reducing emissions.

- Ramping up the adoption of **super-efficient room air conditioners** in homes has the potential to lower the Indian residential sector's operational carbon emissions by an impressive **12%**. This is by far the one measure that has the largest potential to lower the building sector's operational emissions if adoption rates increase over the next 25 years.

- Progressively increasing the adoption of **low-carbon alternatives for cement** in new construction projects has the potential to lower the Indian building sector's embodied carbon emissions associated with cement cumulatively by **1.4 Gt CO_2e**.

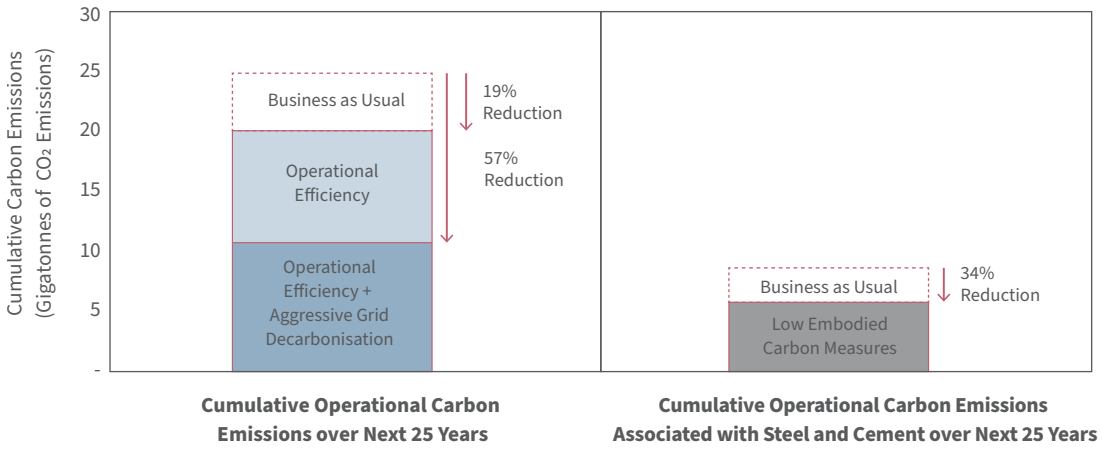
- Progressively increasing the adoption of **low-carbon steel** for new building construction projects has the potential to lower the Indian building sector's embodied carbon emissions associated with steel cumulatively by **1.5 Gt CO_2e**.

These decarbonisation measures together have the potential to eliminate 8 Gt of operational and embodied carbon emissions cumulatively between 2025 and 2050. Implementing them would require a cost premium of 11% or an additional investment of ₹4,566/m^2 (US$52.9/$m^2$) over a business-as-usual scenario. We have assumed that the initial years have higher cost premiums, which then decrease over time as low-carbon technologies are scaled, and we see cost compression in price. Should India's electricity grid undergo a projected decarbonisation of 90% in emission intensity by 2050, this potential emission reduction could rise to an estimated 17 Gt CO_2e.

To put these numbers in perspective, India's annual CO_2 emissions in 2023 were 2.9 Gt CO_2e.[6] Reducing 17 Gt CO_2e cumulatively over 25 years translates to nearly six times India's annual CO_2 emissions in 2023.

Exhibit 1

Potential Operational and Embodied Carbon Emission Reductions in India's Buildings Sector (Cement and Steel, 25 Years)



RMI Graphic. Source: RMI analysis

Roadmap to Decarbonise India's Buildings Sector

More broadly, India's buildings sector can bend the energy growth curve while India's GDP increases and India's electricity sector approaches the 50% renewable energy target to contribute towards India's Nationally Determined Contributions (NDCs) by adopting a whole-system approach. This report presents a comprehensive and actionable roadmap for decarbonising India's buildings sector by aiming to achieve five key objectives:

1. **Establish a Definition of "Net-Zero Carbon Buildings" in India:** A definition for a "net-zero carbon building" is being proposed as a part of this work. The report details a phased approach to meet the requirements of this definition. Standardising the definition of net-zero carbon buildings in India is crucial to ensure consistent understanding, facilitate effective policy implementation, and drive coordinated efforts towards achieving the country's climate goals.

2. **Highlight Impact of five Key Building Decarbonisation Measures Towards Achieving Net-Zero Carbon Buildings in India:** The report details five high-impact building decarbonisation measures that can help new construction projects in India achieve the status of net-zero carbon building as defined in step 1. These five technical solutions were identified through engagement with various stakeholders, market research, and pilot projects, and were based on the maturity of the technology and market readiness.

3. **Quantify the Potential Impact and Associated Cost for the five High-Impact Building Decarbonisation Measures Through Techno-Economic Analysis:** This step involves quantification of the total building sector CO_2 emissions, energy and emission reduction potential, and the total cost of adoption for each of the five high-impact decarbonisation strategies discussed in step 2.

4. **Promote End-User Behaviour Change Interventions for Large-Scale Adoption of the Proposed High-Impact Building Decarbonisation Measures:** A vital aspect of the proposed recommendations is to ensure the end-users/building owners are made aware of the technical solutions being recommended and to encourage personal purchasing choices that ensure at-scale adoption of the recommendations.

5. **Frame National and Sub-National Policy Interventions to Enable Uptake of Proposed High-Impact Building Decarbonisation Measures at the Sector Level:** To ensure the impacts of the proposed five high impact building decarbonisation strategies are fully realised by the sector, an array of national and sub-national policy recommendations are being proposed.

Introduction

India's building stock is growing faster than most places in the world, which could lead to significant regional stresses on energy, water, and other resources. The urban population in India is expected to reach approximately 612.8 million by 2030 and 843.3 million by 2050.[7] Currently, building energy use accounts for 32% of the nation's total energy consumption, increasing by 8% each year.[8] Without proactive energy-efficiency improvements and policy measures, the buildings sector is projected to consume over three times more energy by 2050, with carbon emissions expected to quadruple from 2020 levels.[9]

As India's building stock is set to double in the next two decades, the sector has a crucial role in reducing greenhouse gas emissions and an opportunity to "build right the first time." However, the full value proposition for net-zero carbon buildings remains unfamiliar or undefined for many stakeholders, including owners, builders, investors, and policymakers. Without adequate guidance and roadmaps supported by techno-economic analysis, the sector is likely to revert to past practices. Therefore, mainstreaming net-zero carbon buildings is essential for India to meet its 2030 NDC commitments and achieve net-zero emissions by 2070.

Recognising the significant impact of buildings on national emissions, RMI, in partnership with the National Institute of Urban Affairs (NIUA), published a report titled *From the Ground Up: A Whole-System Approach to Decarbonising India's Buildings Sector*. This report offers a comprehensive perspective on transforming India's building sector, presenting a variety of cost-effective solutions that could reduce CO_2 emissions by over three-quarters by 2050 compared to a baseline scenario, aligning with India's goal of net-zero emissions by 2070. Building on this foundation, the current report aims to develop a roadmap for implementing several high-impact interventions related to embodied carbon, operational carbon, and clean energy, providing multi-sectoral recommendations to mainstream net-zero carbon buildings in India.

Exhibit 2 on the following page shows India's floor area is projected to more than double by 2040. This growth, along with the projected end-of-life of much of today's building stock, suggests that the majority of building stock that will exist in 2050 is yet to be built. The largest share of the new building stock will be residential construction to meet the demands of urban housing and a growing economy, and building sector innovation can improve lives by ensuring energy and environmental sustainability.

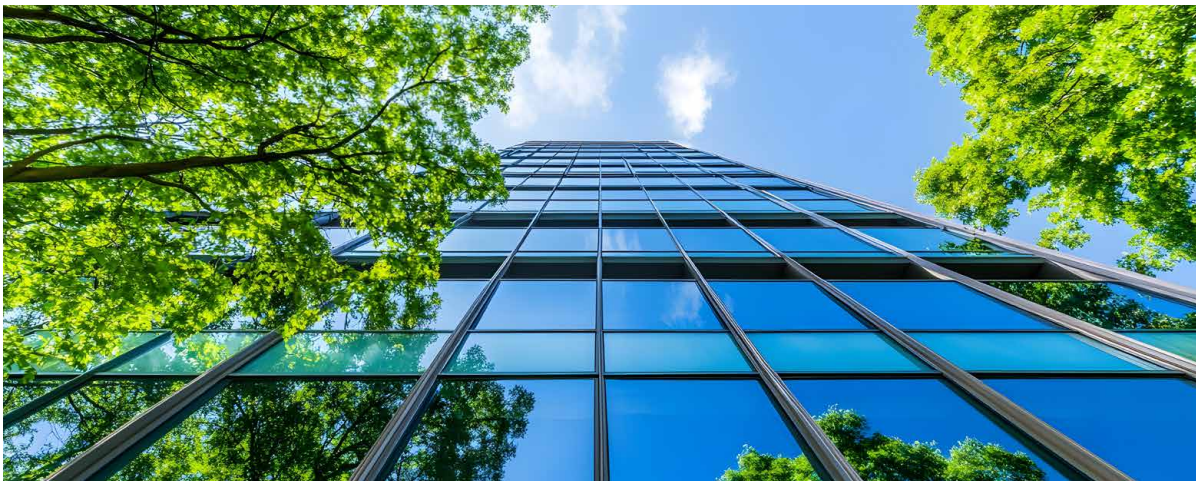
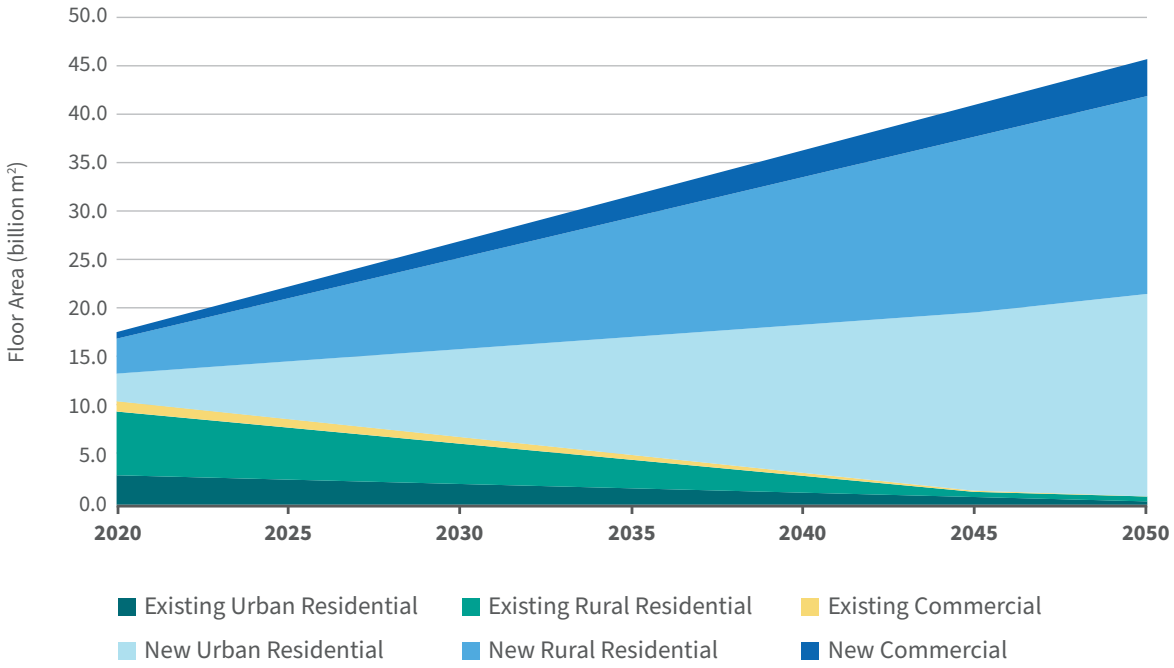


Exhibit 2 **India's Building Stock Projection**



RMI Graphic. Source: RMI analysis.[10]

Mainstreaming net-zero carbon buildings has the potential to deliver vast benefits even beyond climate change mitigation. It will also enhance thermal comfort and productivity, increase resilience, and reduce investments in energy supply infrastructure. It can be done in a manner that is cost-effective and accessible to all.

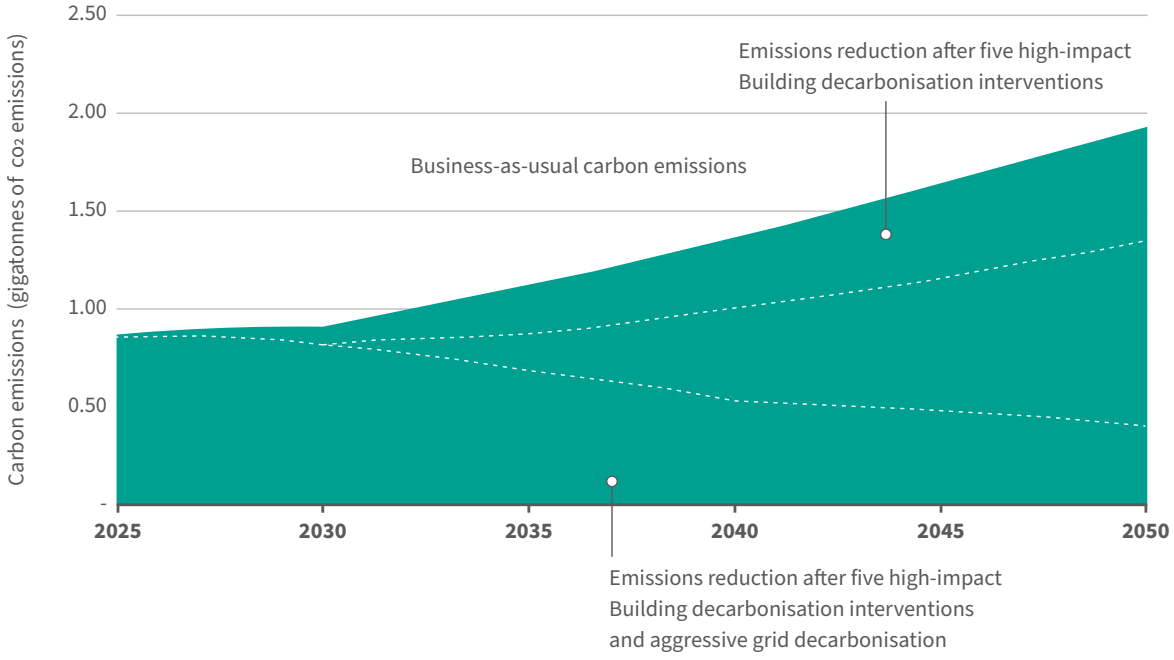
Role of India's Building Sector in India's Climate Goals

Building Right the First Time presents the country with a unique opportunity to transform the buildings sector holistically from design choices, construction materials, and building operations. The leaders in this sector have made tremendous strides in developing a framework to decarbonise this sector through building codes, rating systems, and product standards and labelling. There is a need for a multi-stakeholder approach to scale the array of solutions developed so the building sector can unlock its potential to lower its climate impact while meeting the needs of housing for all set by the Indian government. Based on RMI's analysis, most of India's projected new construction will be in the residential sector. This makes India's residential sector an important part of India's solution to address climate change while providing thermally comfortable and affordable homes to its growing middle class. The most effective way to lower the climate impact of this new construction is to build right the first time.

Exhibit 3

India's Building Sector Floor Space and Carbon Emissions Projections through 2050

Projected Operational and Embodied Carbon Emissions (Cement and Steel use only) from India's Building Sector



RMI Graphic. Source: RMI analysis.

Note: This report uses a subset of the data that was used for the *From the Ground Up* report published by RMI and NIUA. The grid emission factors to calculate the GHG emissions have been updated in the current analysis to reflect latest trends of grid decarbonisation in India.

Exhibit 3 illustrates the baseline operational carbon emissions and embodied carbon emissions associated with cement and steel projected over the next 25 years. The two dotted lines showcase the projected carbon emissions after implementing the high-impact interventions proposed in this report. It is critical to note that embodied carbon emissions are locked in after construction. Hence, it is crucial to adopt low-embodied carbon materials for new construction projects to eliminate the emissions associated with this end-use.

India's building sector is evolving with a focus on sustainability, guided by a combination of building codes and green building rating systems. *The National Building Code* (NBC) and the *Energy Conservation Building Code* (ECBC) provide foundational guidelines for energy efficiency and sustainability, though detailed green building requirements are often addressed through voluntary certification programmes. Prominent green building rating systems include the *Indian Green Building Council* (IGBC) standards, TERI's *Green Rating for Integrated Habitat Assessment* (GRIHA), and *LEED* India. These systems emphasise energy efficiency, water conservation, sustainable material selection, and waste management. Despite the voluntary nature of these guidelines, there is significant progress driven by state-level incentives such as additional floor-area-ratio (FAR) allowances and financial reimbursements for certification fees. States like Punjab, Haryana, and Maharashtra offer various incentives to promote green building practices, reflecting a growing commitment to sustainable development across India.

Developing high-performance buildings (HPBs) in India presents several challenges. High initial costs for

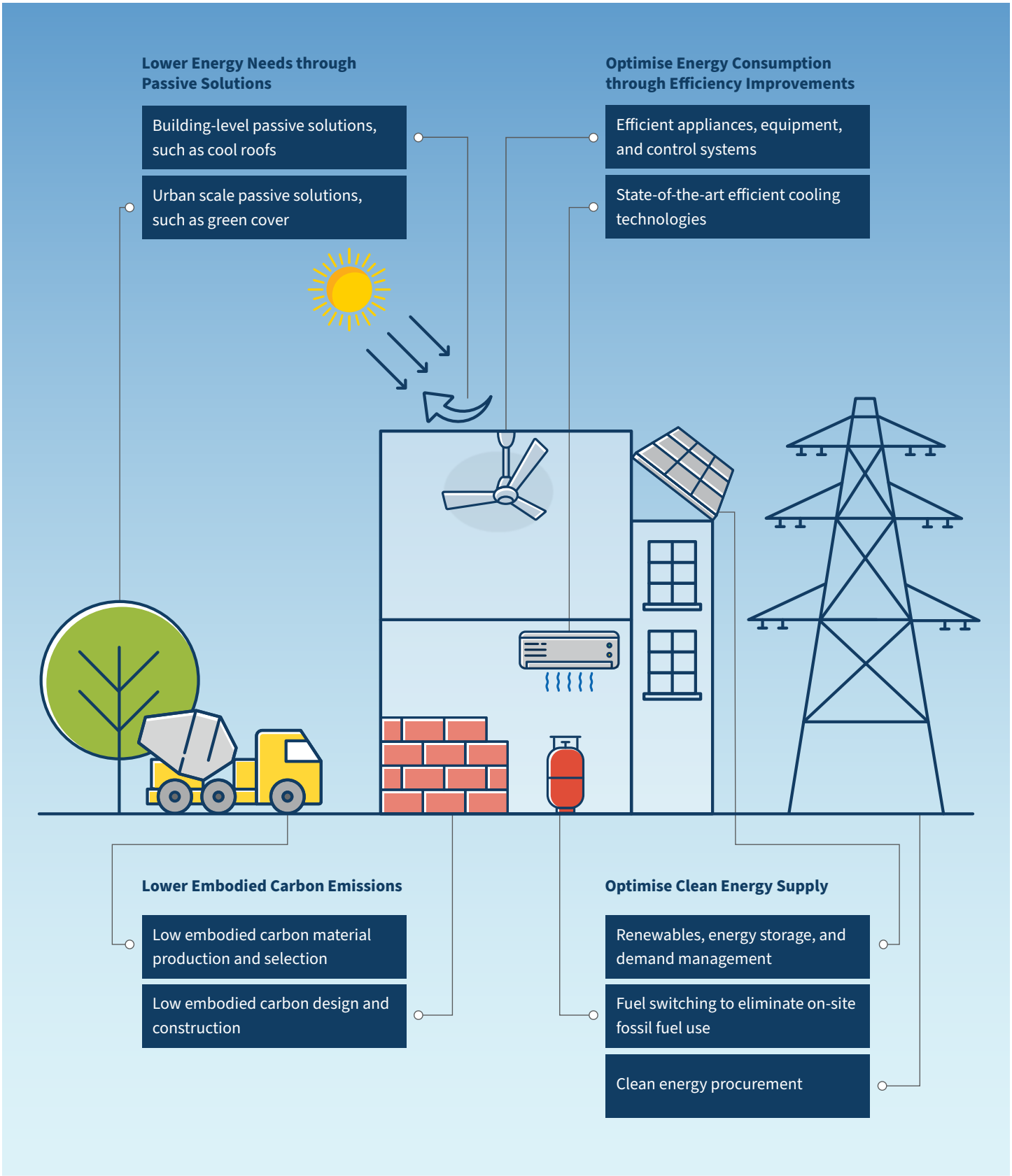
advanced technologies and sustainable materials can deter developers and investors. There is also limited awareness and expertise among builders and architects regarding the benefits and implementation of HPBs. The absence of mandatory nationwide standards leads to inconsistent adoption of sustainable practices, and the slow pace of technological adoption hampers progress. Ensuring compliance with environmental, social, and governance (ESG) standards can be challenging due to the lack of standardised definitions and measurement systems.

Despite these challenges, there are significant opportunities. Government incentives, such as additional FAR allowances and financial reimbursements, encourage the adoption of green building practices. Public-private partnerships can drive innovation and investment in HPBs. Technological advancements in energy-efficient HVAC systems, smart building management, and sustainable materials offer significant potential for improving building performance. Efforts to raise awareness and build capacity among stakeholders can accelerate the adoption of HPBs. Additionally, growing market demand for sustainable and energy-efficient buildings from consumers and businesses can drive the market towards HPBs. By addressing these challenges and leveraging the opportunities, India can make significant strides in developing high-performance buildings, contributing to a more sustainable and energy-efficient future.

This report lays out an actionable roadmap for lowering the carbon emissions of India's building sector through specific high-impact decarbonisation measures that can be scaled. **Exhibit 4** outlines an array of high-impact decarbonisation strategies that can be leveraged to help India's buildings sector achieve these lofty goals.



Exhibit 4 **High-Impact Technical Solutions to Decarbonise India's Building Sector**



RMI Graphic. Source: RMI analysis.

Defining the Term "Net-Zero Carbon Building"

Constructing net-zero carbon buildings is crucial for India, given the significant contribution of the built environment to greenhouse gas emissions and the country's Nationally Determined Contributions (NDCs). To achieve net-zero carbon emissions in the built environment, the first step is to clearly define the term "net-zero carbon building."

The concept of net-zero energy and net-zero carbon buildings has been explored in India for some time now. Various organisations and institutions have proposed definitions tailored to the country's specific context. However, these definitions often diverge in scope and focus, leading to inconsistencies in their calculation methodologies and practical implementation. Many definitions remain theoretical, lacking concrete metrics to assess actual performance. Those that do include metrics often rely solely on on-site energy or metered energy, neglecting critical factors such as transmission losses and the carbon footprint of energy sources. This oversight hinders the development of consistent building standards and effective policy implementation.

Different organisations in India have proposed their interpretations:

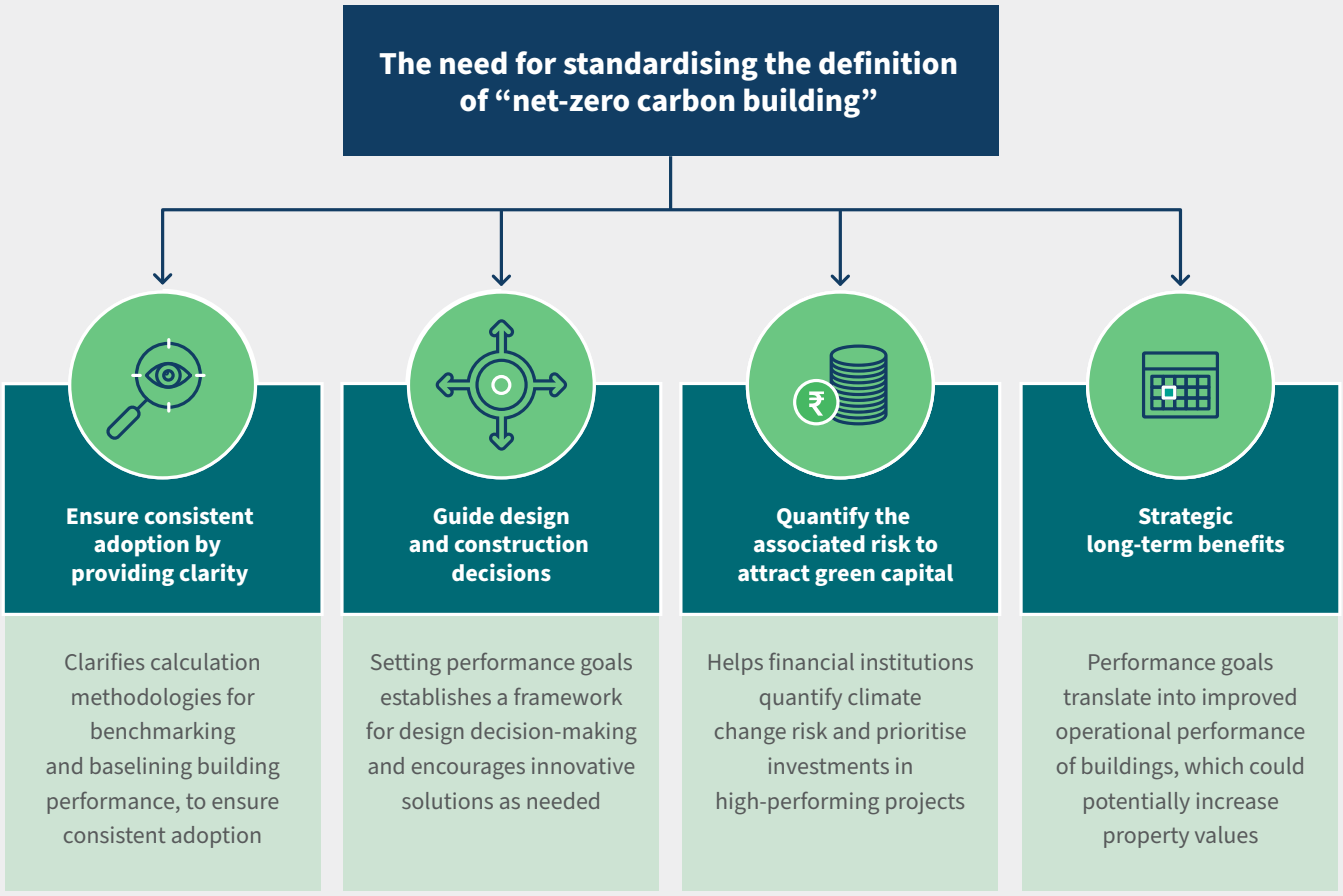
- **Indian Green Building Council (IGBC):** Defines net-zero carbon buildings as those that offset all direct and indirect carbon emissions throughout their lifecycle.
- **Bureau of Energy Efficiency (BEE):** Recognises net-zero energy buildings (NZEBs) and net-positive energy buildings (NPEBs) through its Shunya Labelling Programme.
- **State-level building codes and regulations:** Contributes to the promotion of energy efficiency and sustainability.
- **MAITREE Initiative:** Provides a theoretical definition of site zero energy buildings, which produce at least as much energy as they consume annually.

Although these initiatives are valuable, a clear and universally accepted definition of net-zero carbon buildings in India is still needed to facilitate standardised building codes and effective policies. A comprehensive definition should consider both energy consumption and carbon emissions, incorporating factors like embodied carbon, operational energy, and renewable energy generation. By addressing these nuances, India can accelerate the transition to a sustainable built environment.

Need for Standardising the Definition of a Net-Zero Carbon Building

Creating a unified definition of a net-zero carbon building in India is paramount for several reasons, as shown in **Exhibit 5**. It provides a solid foundation for developing comprehensive policies and strategies to decarbonise the built environment. Furthermore, it addresses the current inconsistencies in definitions and calculation methodologies, ensuring a standardised approach for benchmarking and baselining.

Exhibit 5 **Reasons to Standardise the Definition of "Net-Zero Carbon Building"**



RMI Graphic. Source: RMI analysis

Given India's rapid urbanisation and the projected doubling of floor area by 2040, the urgency of a standardised definition cannot be overstated.[11] This will enable accurate mapping and estimation of the true carbon footprint of buildings, including both operational and embodied carbon. Additionally, it allows the finance industry, investors, and consumers to know what they are funding, investing in, or buying with consistency, serving as a foundation for green mortgages and other financial products. This, in turn, will facilitate the development of targeted interventions and policies to mitigate their environmental impact.

A robust taxonomy should encompass the following key elements:

Definition of Net Zero: A clear and concise definition of a net-zero carbon building incorporating operational and embodied carbon emissions.

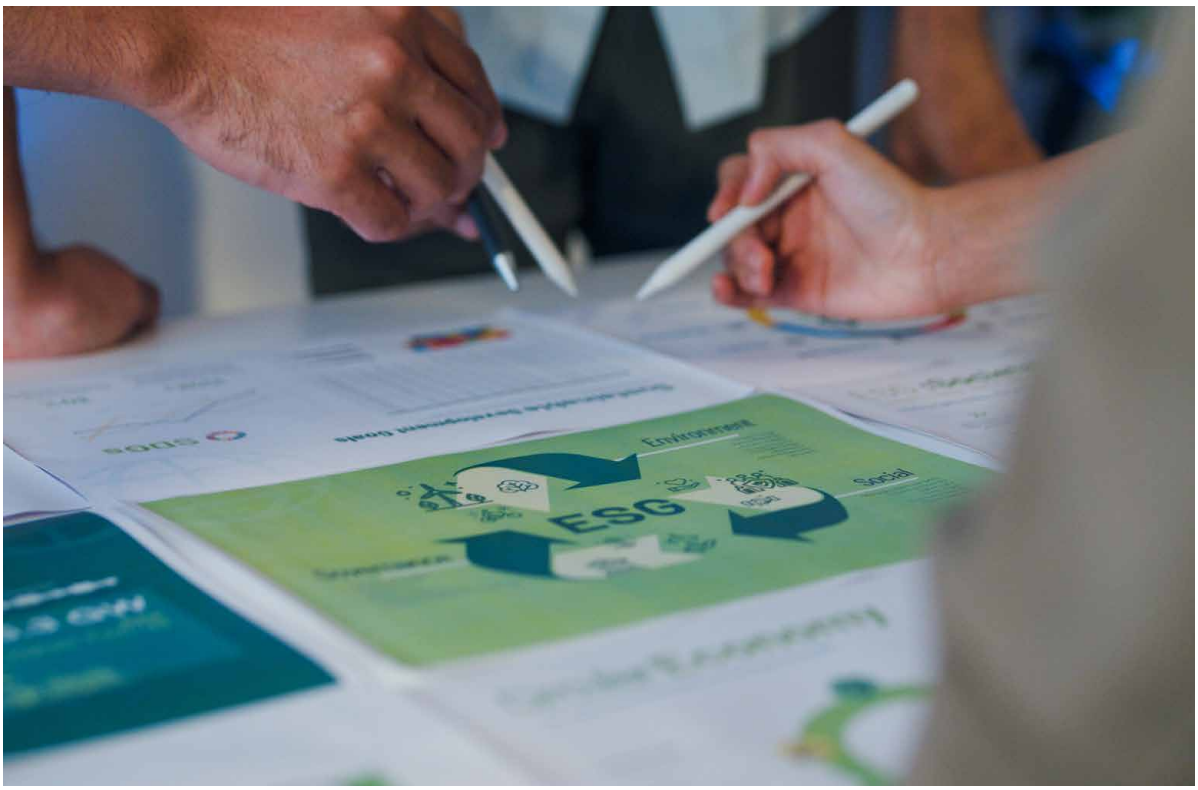
Scope and Boundaries: Guidelines for determining the scope of a building's carbon footprint, including consideration of upstream and downstream activities.

Calculation Methodology: Standardised methodologies for quantifying carbon emissions, incorporating direct and indirect sources.

Offsetting Mechanisms: Criteria for evaluating and accrediting carbon offset projects to compensate for residual emissions.

Verification and Certification: Procedures for verifying compliance with net-zero standards and issuing certifications.

Performance Metrics: Key performance indicators (KPIs) to track progress towards net-zero goals, such as energy efficiency, water consumption, and material use.



Implementing Net-Zero Carbon Buildings in India

Implementing net-zero carbon buildings in India involves various aspects of a comprehensive policy and regulatory framework, as shown in **Exhibit 7**. This includes developing a standardised definition aligned with international best practices and establishing clear guidelines for certification and labelling by government bodies like BEE and the Ministry of Housing and Urban Affairs (MoHUA). Another aspect is mandating energy efficiency for new constructions and renovations, incorporating renewable energy, water conservation, and sustainable materials. Additionally, offering incentives such as tax breaks, subsidies, and green financing schemes encourages investments in energy-efficient technologies and renewable energy systems. Promoting green building certification programmes like IGBC and LEED, with a robust certification process and third-party verification, further incentivises sustainable practices.

Technological advancements are another crucial aspect, promoting low-embodied carbon materials and energy-efficient appliances, integrating renewable energy sources, and implementing smart building technologies. Financial mechanisms, including establishing green bond markets and green banks and encouraging commercial banks to offer green loans, support these efforts. Public-private partnerships foster collaboration and resource leveraging, while innovative financing mechanisms support energy efficiency upgrades. Capacity building and awareness efforts, such as training programmes, public awareness campaigns, and international collaboration, ensure widespread knowledge and expertise. Finally, pilot projects and demonstrations showcase the feasibility and benefits of net-zero buildings, with data collection and analysis identifying best practices and areas for improvement, and knowledge sharing through workshops, conferences, and publications disseminates information on net-zero building technologies and practices.

A comprehensive literature review was conducted to analyse existing definitions of net-zero carbon buildings globally, including the United States, Europe, and India. This review synthesised a wide range of sources, including academic research, policy documents, industry standards, and case studies. The findings from this review, along with the existing body of work in India, informed the development of a tailored definition for net-zero carbon buildings in the Indian context.

Proposed Definition of Net-Zero Carbon Building

A net-zero carbon building is one that employs a comprehensive strategy to minimise GHG emissions linked to its operational energy use within the building's site boundaries. This involves reducing energy consumption through efficient design and technologies. Any remaining yearly GHG emissions caused by operational energy and from refrigerants used for space cooling are then neutralised via on-site or off-site offsets, achieving a net-zero carbon footprint.

Note: Currently, the proposed definition requires only reporting the embodied carbon emissions for a project. Given the limitations of existing policies, the lack of reliable data, and the general unawareness about emissions from building materials, we suggest including embodied carbon in the next iteration of the net-zero carbon definition.

Scope and Applicability of the "Net-Zero Carbon Building(s)" Definition

Achieving net-zero carbon for a building requires a holistic approach that extends beyond operational emissions. A comprehensive definition should encompass not only operational energy but also embodied carbon in materials used to build the facility and refrigerants used for space conditioning over the building's life cycle; this definition currently requires reporting of only the embodied emissions. In addition to the equation detailed in the section above, we propose the following scope and applicability as part of the definition:

- **Building type:** Applicable to new buildings or a group of buildings on a site.
- **Applicability:** The definition shall apply to buildings falling under the scope of the latest Eco Niwas Samhita (ENS) and Energy Conservation Building Code (ECBC) for commercial buildings.
- **Phasing:** The first version of the definition shall apply to building operational carbon emissions only. In subsequent versions, we recommend including embodied carbon of key materials like cement and steel.
- **Reporting Criteria:** Reporting for embodied carbon and emissions is mandatory (A1-A5); refer to the Appendix for details.

Note: Although current criteria are based on ENS 2018, the upcoming ENS 2024 draft encompasses a broader scope. The final criteria will be determined by the code in effect at the time of the project.



Exhibit 7 **Key Aspects of Implementing Net-Zero Carbon Buildings in India**



RMI Graphic. Source: RMI analysis.

Roles of Key Stakeholders in Net-Zero Building Implementation

Governmental bodies could play a pivotal role in implementing net-zero carbon buildings in India. The Bureau of Energy Efficiency (BEE) could strengthen energy labelling programmes, conduct capacity-building workshops, monitor compliance with energy standards, collaborate internationally, and support research and development. MoHUA can formulate policies, provide financial incentives, organise training programmes, mandate net-zero standards for government projects, and fund research. Urban local bodies (ULBs) and Urban development departments (UDDs) could enforce local regulations, incorporate net-zero principles into planning, develop necessary infrastructure, and conduct public awareness campaigns.

Industry professionals, including developers and designers, could be crucial for designing and constructing net-zero buildings, selecting low-carbon materials, integrating renewable energy systems, and optimising building operations. They could also pursue green building certifications to enhance project value. Occupants could contribute by adopting energy-efficient behaviours, participating in energy-saving programmes, choosing efficient appliances, and supporting building management efforts to reduce energy waste. Together, these stakeholders could ensure the successful implementation of net-zero carbon buildings in India.

Quantifying the Savings and Cost of Recommended High-Impact Building Decarbonisation Measures

Modelling Framework of Techno-Economic Analysis

The techno-economic model developed in this report is designed to estimate the costs and benefits of adopting solutions to reduce the climate impact of space cooling and building materials — specifically, the potential CO_2 emissions reductions — within India's building sector. By conducting energy and emissions reduction calculations on a per unit area (per m^2) basis of new construction, the model utilises stock modelling developed by researchers at the *Lawrence Berkeley National Laboratory* (LBNL) and RMI and builds on their stock analysis. The study identified five high-impact technical decarbonisation strategies for national-scale implementation.

For each high-impact building decarbonisation measure, potential emissions reductions and sector-level costs were estimated by comparing three scenarios:

- **Business-as-usual scenario:** This is the baseline scenario where India's building sector progresses as usual with the measures adopted at baseline rates by the building sector over 25 years.

- **Intervention scenario:** This reflects a scenario where the proposed building decarbonisation measures are adopted at scale by India's building sector while India's grid progresses based on the current grid decarbonisation policies in place.

- **Aggressive grid decarbonisation scenario:** This reflects a scenario where the proposed building decarbonisation measures are adopted at-scale by India's building sector and India's grid is aggressively decarbonised with its emissions intensity dropping by 90% over 25 years.

A detailed bottom-up analysis was performed for each intervention to estimate potential emissions reductions and implementation costs per building. These values were then scaled to the sector level using LBNL's stock model for India's building sector. Rather than being an exercise in predicting the future, this analysis aims to provide a range-based assessment of potential benefits of high impact measures relying on current information. By offering these insights, the report hopes to guide the strategic implementation of decarbonisation strategies across India's growing building sector.

A few key assumptions made for the modelling exercise are listed below. In addition to the high-level assumptions below, a detailed list of modelling assumptions is included in the Appendix.

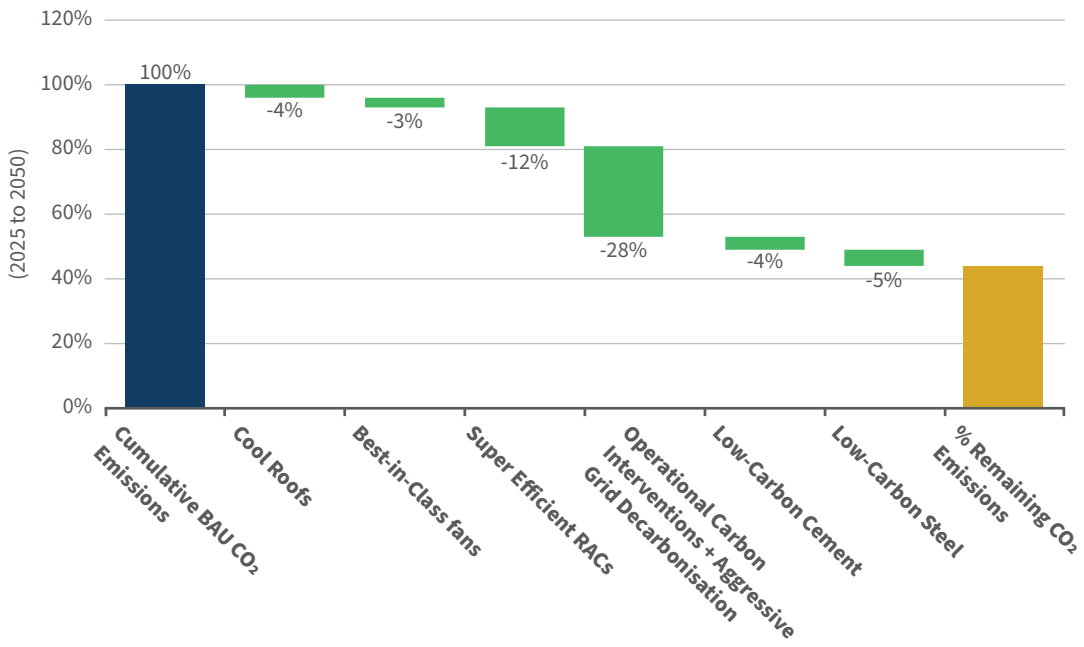
- India's urban residential, rural residential, and commercial building stock is projected to more than double over the next 25 years.

- Cool roofs are assumed to have a baseline penetration of 5% in 2025 and linearly scale up to 100% penetration by 2035 in the intervention scenario for the entire buildings sector.
- 5-star ceiling fans are assumed to have a baseline penetration of 3% in 2025 and linearly scale up to 100% penetration by 2035 in the intervention scenario for the entire buildings sector.
- Super-efficient room air conditioners (RACs) are assumed to have a baseline penetration of 0.5% in 2025 and exponentially scale up to 100% penetration by 2035 in the intervention scenario for the entire buildings sector.
- Cement manufactured through low-carbon methods is assumed to have 0% penetration in 2025 and linearly ramp up to achieve 100% penetration in the buildings sector by 2043.
- Steel manufactured through low-carbon methods is assumed to have 0% penetration in 2025 and is projected to linearly ramp up to achieve 100% penetration in the buildings sector by 2050.

Key Takeaways from the Techno-Economic Analysis

Exhibit 8

Decarbonisation Potential of the five High-Impact Decarbonisation Interventions



RMI Graphic. Source: RMI analysis.

The modelling results highlight the transformative potential of the proposed five decarbonisation measures for India's building sector. These measures could collectively eliminate 8 Gt of CO_2e (Gt CO_2e) of operational and embodied carbon emissions from 2025 to 2050. This ambitious reduction can be achieved with a cost premium of 11.13%, translating to an additional investment of ₹4,566/m^2 (US$52.9/$m^2$) over a business-as-usual scenario. If India's electricity grid decarbonises as projected, the potential emission reduction could rise to an estimated 17 Gt CO_2e. To put these **Exhibits** into perspective, India emitted 2.9 Gt of CO_2 in 2023. Thus, reducing 16 Gt CO_2e over 25 years is equivalent to approximately 6 times India's annual emissions in 2023.

Adopting cool roofs in new building construction could lower operational carbon emissions by 4%. The models assume a phased adoption over time. Replacing traditional fans with 5-star fans in new construction projects could reduce operational carbon emissions by 3%. Increasing the adoption of super-efficient room air conditioners in homes could lower operational carbon emissions in the residential sector by an impressive 12%. This measure has the largest potential to reduce operational emissions if adoption rates increase over the next 25 years. Progressively adopting low-carbon alternatives for cement in new construction projects could reduce embodied carbon emissions associated with cement by 1.4 Gt CO_2e. Increasing the adoption of low-carbon steel for new building construction projects could lower embodied carbon emissions associated with steel by 1.5 Gt CO_2e.

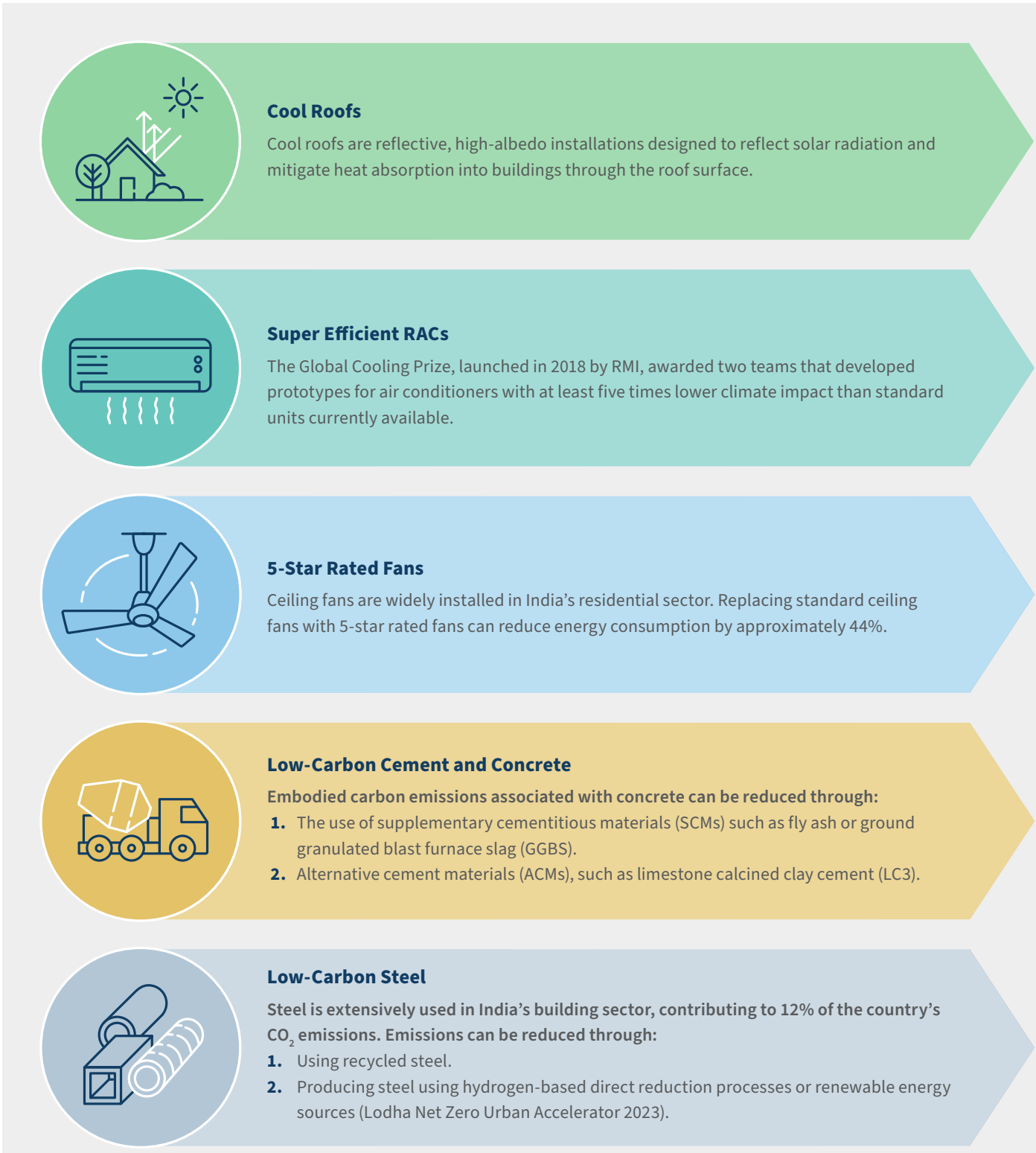
Cumulatively, these interventions can reduce operational carbon emissions by 19% for the entire built environment over 25 years. If India's grid is aggressively decarbonised, the operational carbon emissions can be lowered by an additional 38%. Additionally, the two low-embodied carbon interventions can reduce emissions from the use of steel and cement in buildings. These measures, when implemented in combination, represent a significant step towards a more sustainable and low-carbon future for India's building sector.

Recommended High-Impact Decarbonisation Measures for India's Buildings Sector

Building operations in India account for a third of its energy use. Additionally, about 10% of the country's energy is used in the production of building materials and construction of new buildings.[12] This report delves into the change model that can be adopted at the national and sub-national levels to encourage the adoption of the five decarbonisation strategies listed below in **Exhibit 9**. The five decarbonisation strategies for implementation were selected based on their market readiness, GHG reduction potential, and ease of adoption. In subsequent sections, this report presents a roadmap to scale these five high-impact decarbonisation measures for India's buildings sector, as summarised in the **exhibit** below.



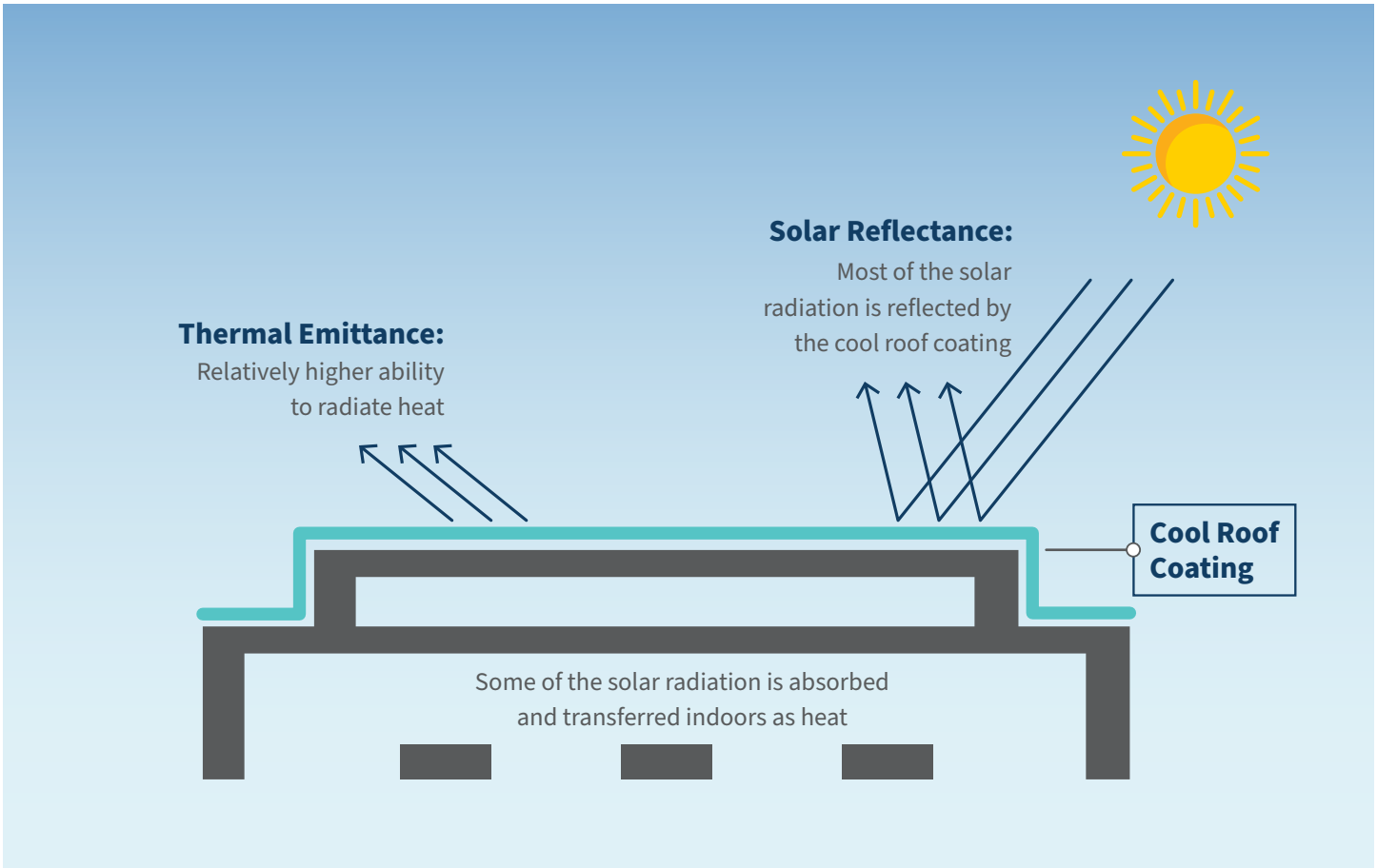
Exhibit 9 **Five High-Impact Decarbonisation Measures for India's Buildings Sector**



RMI Graphic. Source: Global Cooling Prize by Mission Innovation and RMI and Gateway to India's Dymaxion, Lodha and RMI India Foundation, 2023.[13]

Cool Roofs

Exhibit 10 **Passive Cooling Through Cool Roof Coatings**



RMI Graphic. Source: RMI analysis.

What Are Cool Roofs?

Cool roofs are a simple and effective passive measure that can be adopted in residential buildings to handle extremely hot temperatures. A cool roof is one that strongly reflects the sunlight (solar energy) and cools itself by efficiently emitting any heat that is absorbed. The roof reduces the amount of heat conducted into the building below by staying cooler. This is achieved by overlaying the roof with materials/coatings with specific physical properties:

- **High solar reflectance:** The fraction of solar energy that is reflected by the roof (measured on a scale from 0 to 1)
- **High thermal emittance:** The relative ability of the roof surface to radiate heat (measured on a scale from 0 to 1).

This ensures that a minimum amount of heat is absorbed into the space through the roof, and indoor air temperatures for spaces directly under the roof can be lowered by up to 2.1 to 4.3°C.[14] The material used to cover the cool roof surface can be tiles, paint, or membranes.

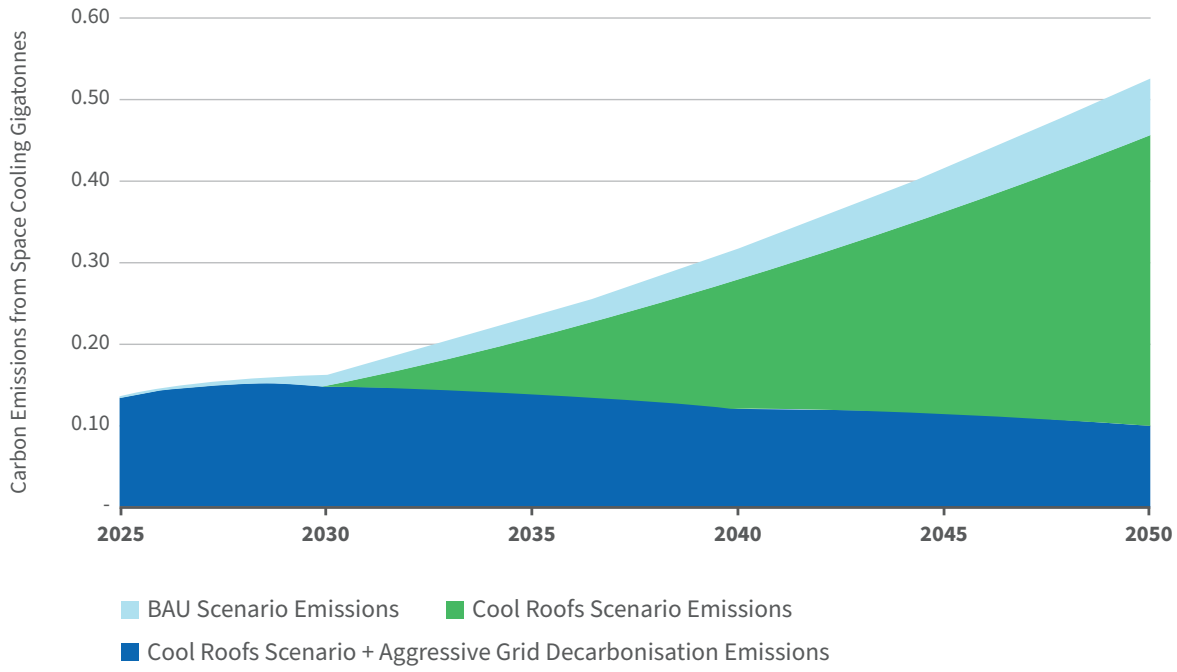
Why Are Cool Roofs Important for India's Buildings Sector?

It is estimated that nearly half of India's population will be living in urban areas by the end of the decade and a large section of this population lives in informal or self-built settlements or slums. Indoor air temperatures of these communities have been found to be a median of 3.6°C hotter inside than outside.[15] As chronic heat waves become more prevalent in Indian cities, this population is left vulnerable to deadly heat conditions.[16] Extreme heat also reduces labour productivity and impacts the economy by disrupting trade.[17] Based on an analysis by RMI, when adopted at scale, cool roofs could save thousands of lives in India alone by 2030.[18] Further, cool roofs could add a cumulative ₹1.89 lakh crore (US$22 billion) to India's economy by 2030 by enhancing living conditions.[19] The Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, published the — *India Cooling Action Plan,* a national document that recommends cool roofs as an effective passive solution to lower cooling needs, specifically in housing for economically weaker sections and low-income groups.[20]

Key Takeaways

Exhibit 11

Potential Mitigated CO_2 Emissions from India's Building Sector by Adopting Cool Roofs



RMI Graphic. Source: RMI analysis.

Cool roofs are a simple yet powerful innovation to ensure India's buildings are significantly cooler and more energy efficient.

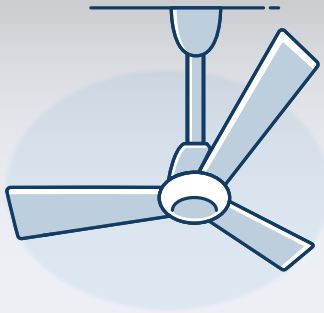
By 2025, a modest 5% of buildings will start to adopt cool roofs.[21] It is assumed that this number will steadily grow, reaching full adoption by 2035 for this model. As more buildings embrace this technology, the benefits become increasingly evident. On average, buildings with cool roofs experience a 14% reduction in energy consumption.

Over a span of 25 years, from 2025 to 2050, the cumulative effect of cool roofs is profound. The energy consumption of India's building sector drops by approximately 2,000 TWh, a significant achievement given the sector's vast scale. This reduction in energy use translates to a 1 Gt decrease in CO_2 emissions under current policies to decarbonise India's electricity grid. If the grid is Aggressively decarbonising the grid to be 90% clean by 2050, this would correspond to a 1.4 Gt reduction in CO_2 emissions.

5-Star Ceiling Fans

Exhibit 12

5-Star Fans Can Provide Thermal Comfort More Efficiently than Conventional Fans



- BEE rates ceiling fan efficiency using service value, which is calculated by dividing air delivery (m^3/min) by power consumption (W).
- Ceiling fans with service value greater than or equal to 4 are awarded a 5-Star BEE rating.

RMI Graphic. Source: RMI analysis.

What Are 5-Star Ceiling Fans?

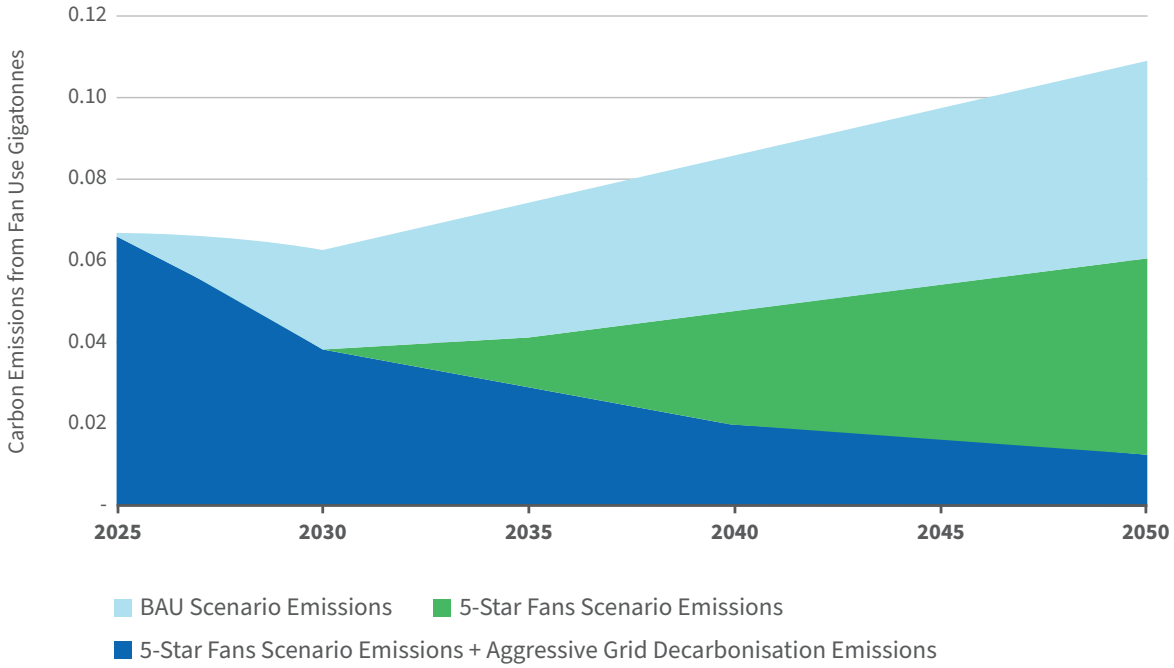
The Bureau of Energy Efficiency rates the performance of ceiling fans based on a metric called service value. The service value of ceiling fans is calculated by dividing the fan's air delivery in cubic metres per minute by its power consumption. For example, a fan delivering 220 m^3/min while using 50 W has a service value of 4.4. Ceiling fans with a service value greater than 4 receive a BEE 5-star rating.[22] BLDC fans are one such modern innovation in fan technology that falls in this category and was considered for this study. They utilise brushless DC (BLDC) motors that have significant benefits — easy controllability, high efficiency, and longer life span. These motors are also electronically communicated (i.e., the utilise on-board electronics to control the motor) resulting in lower operating costs.[23] Replacing traditional motors with BLDC motors makes ceiling fans very efficient, with lower operating costs and longer lifespans.[24]

Why Are 5-Star Fans Important for India's Buildings Sector?

Nearly 90% of households in India have ceiling fans installed, and only an estimated 3% of them are of a super-efficient type. Conventional ceiling fans consume 75–80 W, whereas 5-star rated fans consume approximately 44% less energy. Hence, large scale replacement to 5-star fans presents an opportunity to lower India's electricity consumption.[25] This translates to energy cost savings for consumers, ensuring an affordable cooling solution. The 5-star fans are also smoother and quieter to operate than traditional ceiling fans. India's Ministry of Power announced the "Energy-Efficient Fans Programme (EEFP)" in November 2023 in collaboration with Energy Efficiency Services Limited (EESL) and the Bureau of Energy Efficiency (BEE). The programme aims to mainstream the use of 5-star fans in India's residential sector by distributing 10 million super-efficient fans.

Exhibit 13

Potential Mitigated CO_2 Emissions from India's Building Sector from 5-Star Fans



RMI Graphic. Source: RMI analysis.

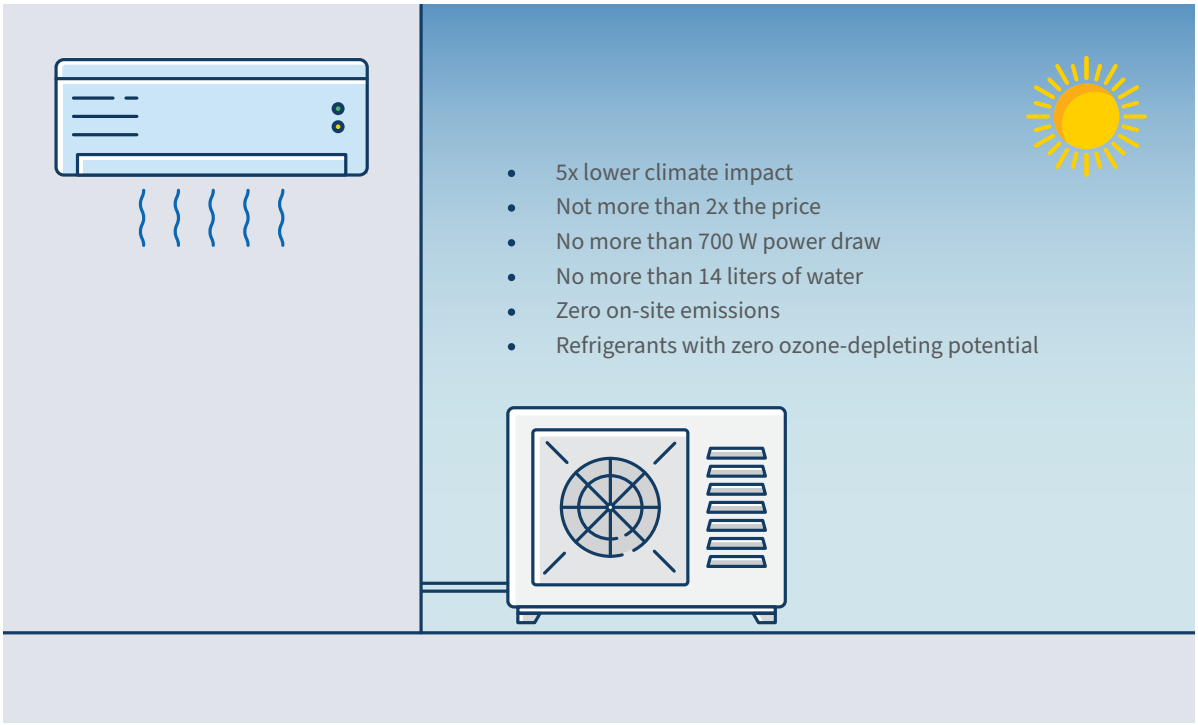
Ceiling fans are critical in providing thermal comfort in most Indian households. Transitioning to 5-star fans presents a significant opportunity for energy savings across the sector.

By 2025, it is assumed that 0.5% of ceiling fans will be 5-star, with this percentage gradually increasing to 100% by 2035. These fans, being 44% more efficient on average than traditional fans, hold great potential for energy reduction. Modelling estimates suggest that a full transition to 5-star fans at the sector level could save approximately 1,700 TWh of energy, leading to a 0.8 Gt reduction in CO_2 emissions from 2025 to 2050 with the current grid decarbonisation policy in place. Aggressively decarbonising India's grid to be 90% clean in 2050 would correspond to 1.3 Gt lower CO_2 emissions over the next 25 years.

Super-Efficient Room Air Conditions

Exhibit 14

Super-Efficient Room Air Conditioners Are an Important Active Cooling Solution



RMI Graphic. Source: RMI analysis.

What Are Super-Efficient Room Air Conditioners?

Super-efficient RACs provide thermal comfort with a much smaller environmental footprint than current air conditioner models — they consume less energy and use eco-friendly refrigerants. Traditionally, the Bureau of Energy Efficiency (BEE) assigns a star rating to electronic appliances to help buyers understand their energy efficiency. The star ratings range from 1 (lowest efficiency) to 5 (highest efficiency). In India, 5-star air conditioners are essential due to their high energy efficiency, which results in significant savings on electricity bills, a reduced environmental footprint, and enhanced performance with features like inverter technology and superior air filtration. These advantages align with government regulations and incentives promoting energy-efficient appliances, making 5-star RACs a wise choice for consumers, balancing cost, performance, and sustainability.

In late 2018, a broad-based coalition led by RMI, the Government of India's Department of Science and Technology, and Mission Innovation launched the *Global Cooling Prize* with the ambitious goal of developing a state-of-the-art, highly efficient, climate-friendly solution that is also affordable. The Global Cooling Prize spurred innovation in super-efficient cooling solutions focused on India, with winners showcasing technologies that surpassed the efficiency of 5-star air conditioners currently on the market. These technology pilots were subsequently tested on site by the RMI team in collaboration with various stakeholders. The modelling inputs used for the analysis in the current report were validated against the measured performance of the equipment during these on-site tests, ensuring the accuracy and reliability of findings. The most important aspect of a super-efficient RAC is its ability to deliver efficient dehumidification without significantly overcooling the space.

Field testing conducted by the Global Cooling Efficiency Accelerator in partnership with Lodha Group in India found that super-efficient ACs consume 50% less energy than 3-star ACs and 30% less than 5-star ACs. If we consider the hours when 3-star ACs do not meet the indoor humidity target, the energy savings would be much higher. Furthermore, super-efficient air conditioners draw up to 50% less peak power than traditional 3-star units. This significant reduction in energy consumption and peak power draw can positively impact the development of electric grid infrastructure as the adoption of room ACs grows in India.[26]

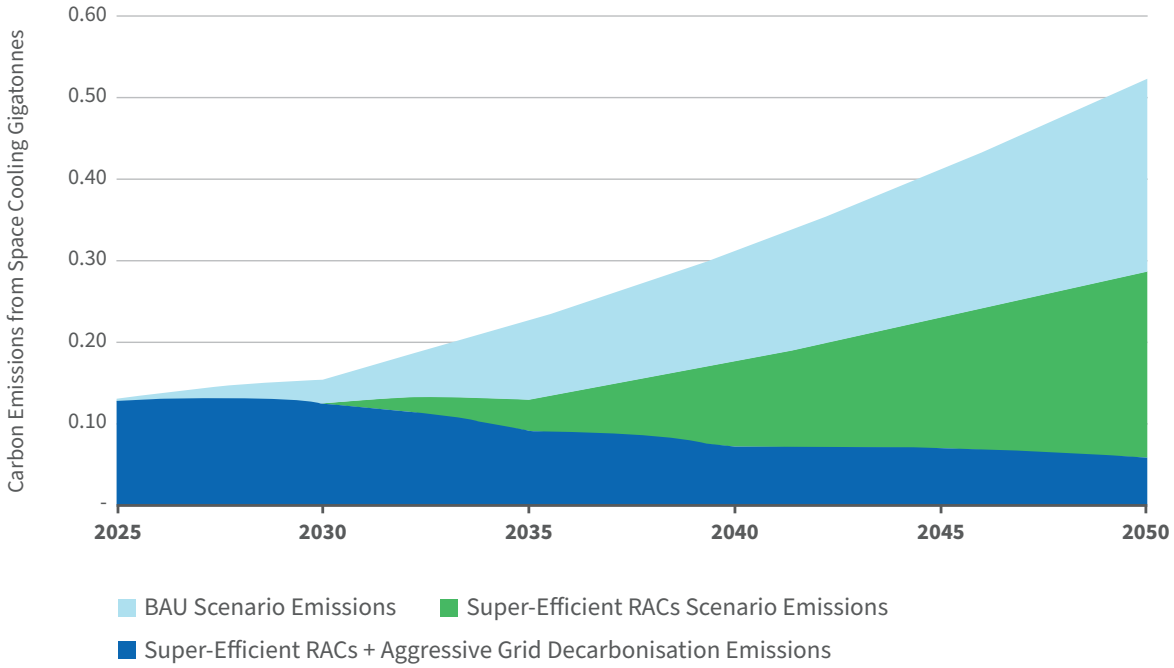
Why Are Super-Efficient Room Air Conditioners Important for India's Buildings Sector?

With growing temperatures and rapid urbanisation, India's demand for cooling is increasing significantly. Currently, 3-star RACs are the most prevalent for residential usage in India.[27] However, these air conditioners are energy intensive and contribute to high electricity demand and further aggravate the climate impact of the buildings sector. Switching from conventional ACs to super-efficient ACs could significantly lower the energy consumed for cooling India's residential sector. According to an analysis, this switch could potentially prevent an additional 2,000 GW of power generation capacity in India.[28] As the climate warms and becomes more humid, air conditioners will need to handle more latent loads, making dehumidification performance crucial for occupant comfort and preventing high energy bills during hot and humid seasons.



Exhibit 15

Potential Mitigated CO_2 Emissions from India's Building Sector from Super-Efficient RACs



RMI Graphic. Source: RMI analysis.

Super-efficient room air conditioners are critical for reducing energy consumption and mitigating climate change impacts, as demonstrated through the Global Cooling Prize. These innovative air conditioners have been shown to save over 50% of cooling energy in typical residential buildings. We can estimate substantial benefits by assuming that their adoption gradually reaches 100% by 2035.

The modelling exercise suggests that widespread use of super-efficient RACs could avoid to approximately 6,000 TWh in operational energy consumption in the building sector, translating to a 2.9 Gt decrease in CO_2 emissions over 25 years with the current progress in decarbonising India's electricity grid. Aggressively decarbonising the grid to be 90% by 2050 would correspond to 4.1 Gt lower CO_2 emissions.

In essence, super-efficient air conditioners offer a feasible pathway to significantly cut down energy usage and carbon emissions to ensure a cooler, greener future.

Low-Carbon Cement

Exhibit 16

Low-Carbon Cement Solutions Can Help Lower Embodied Carbon Emissions



Decarbonisation Measures for Cement and Concrete:

- **Improving energy efficiency** of all life-cycle phases (manufacture, transport, etc.)
- **Substituting clinker** with alternative cementitious materials
- **Decarbonising the grid** to lower carbon emissions from cement manufacture

Embodied Carbon Emissions from Cement Can Be Lowered by Using:

1. Supplementary cementitious materials (SCMs) such as fly ash or ground granulated blast furnace slag (GGBS)
2. Alternative cement materials (ACMs) such as limestone calcinated clay cement (LC3)

RMI Graphic. Source: RMI analysis.

What Are Low-Carbon Cement Alternatives?

There are several promising low-carbon cement/concrete solutions that can help reduce their embodied carbon footprint:

- Reducing clinker content in cement by using supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume can help reduce the overall carbon footprint.
- Alternative cementitious materials (ACMs) such as limestone calcined clay cement (LC3) are a cost-effective and energy-efficient alternative to traditional Portland cement in concrete mixes. LC3 combines limestone and calcined clay to reduce the amount of clinker required, thereby lowering CO_2 emissions.
- Optimising concrete mixes to use less cement while maintaining strength and durability (i.e., using less cement and replacing primary/virgin materials with recycled concrete aggregates or industrial by-products).
- Enhancing the energy efficiency of cement production processes can also contribute to lower carbon emissions.
- Other strategies include adopting low-embodied carbon design and construction techniques. This could include developing optimal, modular designs to optimise the material's use.

Why Are Low-Carbon Alternatives to Cement Important for India's Buildings Sector?

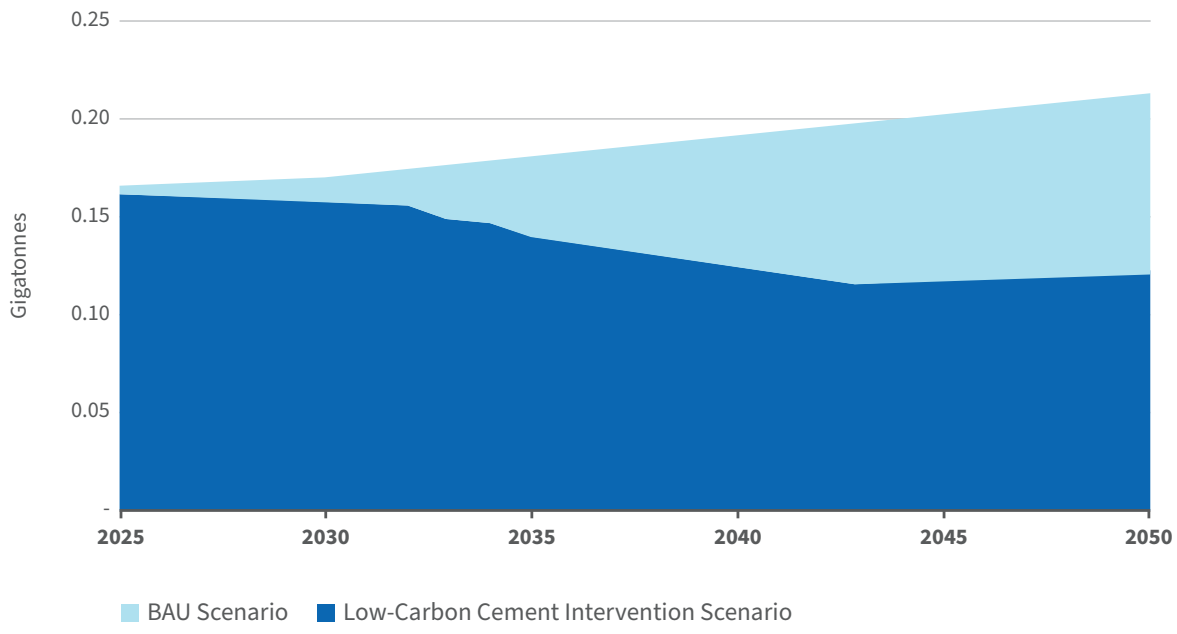
Cement production significantly contributes to India's carbon emissions and was approximately 5.8% of the nation's total CO_2 emissions in 2022.[29] With India's total building floor area projected to more than double in the next 20 years and most of this growth occurring in the urban residential sector, the importance of low-carbon cement and concrete alternatives becomes clear.

India stands at a pivotal moment, as the country is projected to more than double its built floor area by 2050.[30] Without measures to lower embodied carbon emissions, new building construction could lock in high emissions in the sector. Therefore, adopting low-carbon cement alternatives is a vital decarbonisation strategy, given the potential impact such alternatives can have on emissions reduction in the buildings sector.

Key Takeaways

Exhibit 17

Potential Mitigated CO_2 Emissions from India's Building Sector by Adopting Low-Carbon Cement Options



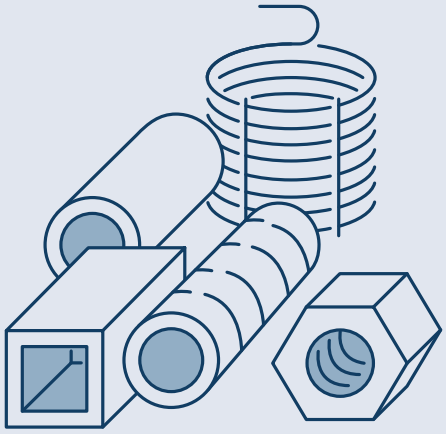
RMI Graphic. Source: RMI analysis.

In the rapidly evolving landscape of India's construction industry, the shift towards low-carbon cement is emerging as a pivotal strategy for sustainable development. This transition is not just a technical adjustment but a significant step towards reducing the environmental impact of the building sector. Modelling results indicate that by progressively adopting low-carbon cement alternatives, the building sector can eliminate 29% or 1.4 Gt of the embodied carbon emissions associated with traditional cement use.

Low-Carbon Steel

Exhibit 18

Low-Carbon Steel Is a Critical Solution to Lower Embodied Carbon Emissions from the Building Sector



Steel production contributes to 12% of India's CO_2 emissions. This sector can be decarbonised by:

1. Adopting green hydrogen or renewable energy sources to power the steel sector
2. Recycling scrap steel
3. Improving energy efficiency in the steel manufacturing process
4. Adopting carbon capture, utilisation, and storage (CCUS) in the steel industry

RMI Graphic. Sources: RMI analysis.

What Is Low-Carbon Steel?

The steel manufacturing sector accounts for 34% of India's industrial carbon emissions (12% of India's total emissions).[31] Steel manufacturing is the most carbon-intensive phase in steel's life cycle.

The use of technologies such as green hydrogen, renewable energy, and circular practices in steel production can help lower the embodied carbon emissions associated with steel.

The primary means of lowering embodied carbon emissions associated with steel include:

- Switching to greener sources of energy (such as green hydrogen, renewable sources, etc.) to manufacture steel.
- Incorporating circularity in the steel industry using electric arc furnaces (EAF) to reuse scrap steel.

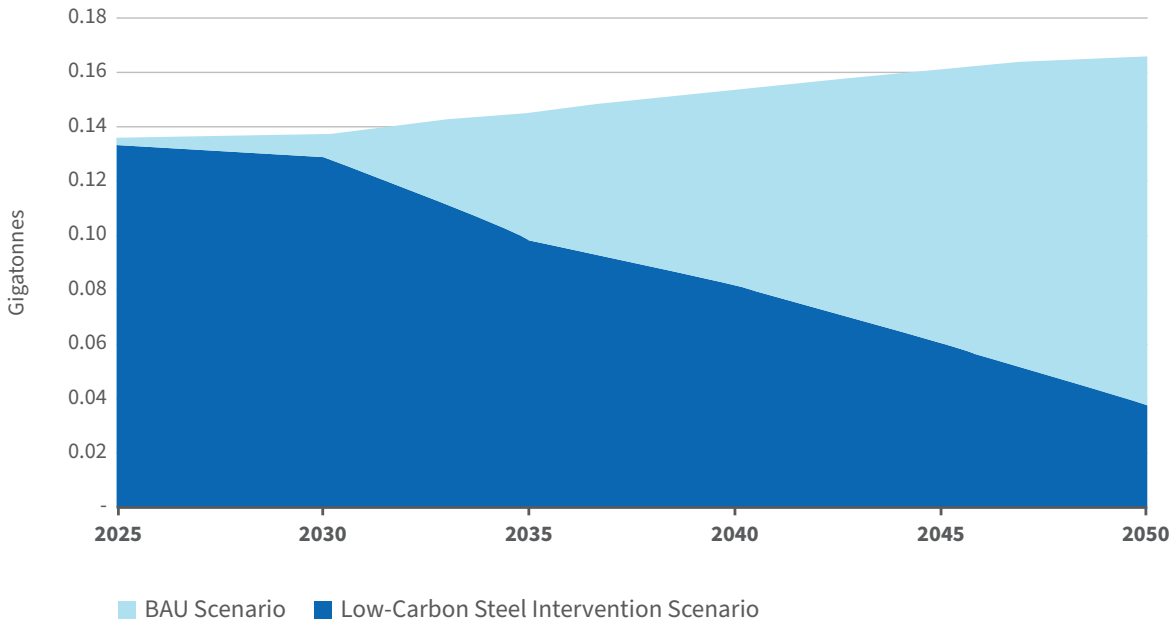
Why Is Low-Carbon Steel Important to India's Buildings Sector?

Traditional steel manufacturing methods are highly carbon-intensive, making it essential to find greener alternatives. As India continues to urbanise, the demand for construction-grade steel is expected to rise steeply. This growth could lead to a substantial increase in embodied carbon emissions associated with steel unless low-carbon alternatives are adopted. India's National Steel Policy, developed by the Ministry of Steel, projects the country's steel industry will manufacture 255 million tonnes of crude steel by 2030-31.[32] Approximately 43% of this steel in India is used in the building construction sector.[33] Given the projected need for construction activities in the coming decades, it is crucial to ensure that low-carbon steel is adopted at scale by the construction sector to lower its climate impact.

Key Takeaways

Exhibit 19

Potential Mitigated CO_2 Emissions from India's Building Sector by Adopting Low-Carbon Steel Options



RMI Graphic. Source: RMI analysis.

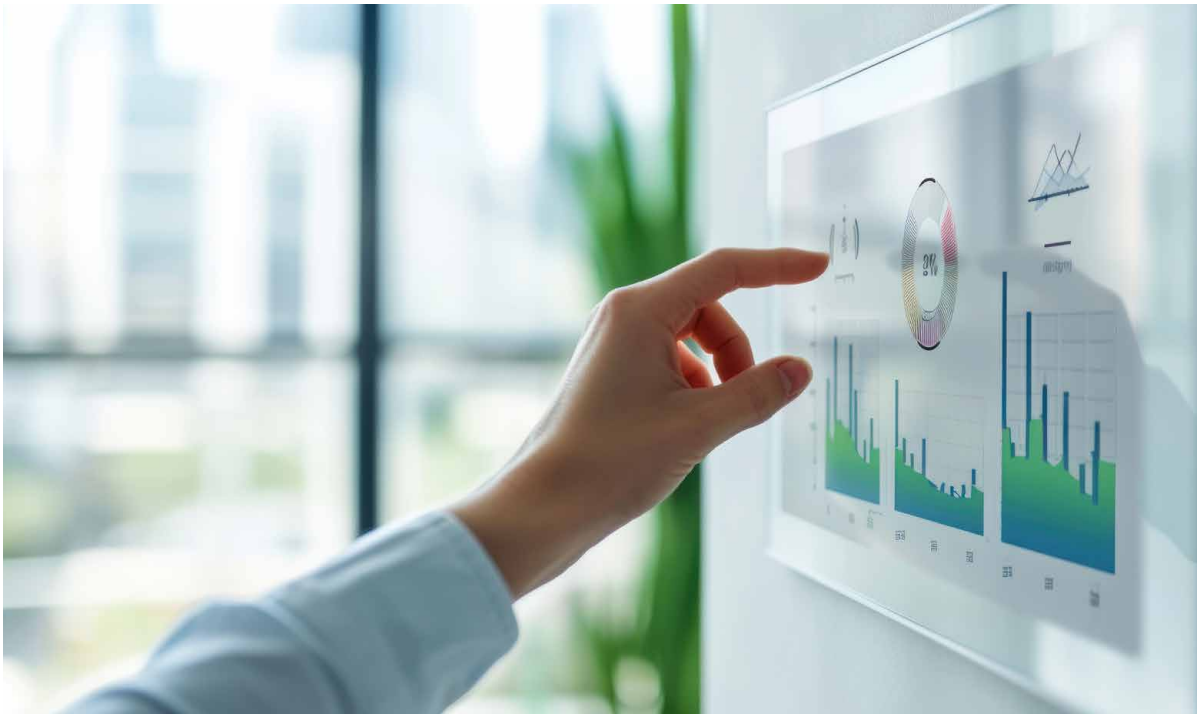
Transitioning to low-carbon steel is crucial for India's building sector, and the modelling results highlight its significant impact. By gradually adopting low-carbon steel from 2025 to 2050, the sector can reduce carbon emissions associated with steel by 40% or 1.5 Gt. This substantial decrease in emissions is vital for mitigating the environmental impact of the construction industry. By adopting low-carbon steel, India can ensure that its rapid urbanisation and infrastructure development are aligned with global climate goals.

Proposed Behavioural Change Intervention Framework

Behavioural change interventions, both in India and globally, aim to promote healthier lifestyles and address public health challenges. These interventions often use techniques like goal setting, feedback, social support, and education to encourage positive behaviours. Addressing the need for behavioural change interventions in India's building sector is, hence, a critical step to meeting net-zero targets. Although technological innovations such as 5-star fans and 5-star RACs are crucial, end-user behaviour is equally important to ensure these technologies are adopted at scale. Several behavioural challenges impede the adoption of efficient technologies, including limited awareness of energy efficiency and its non-energy benefits, inadequate information, biases in interpreting data, and lifestyle choices.

The key stakeholders involved with the five high-impact building decarbonisation measures recommended in this report range from individual homeowners to developers to policymakers. Hence, an array of behavioural change interventions is needed to cater to a wide range of India's building sector stakeholders. The Government of India's Lifestyle for Environment (LiFE) mission is aimed at encouraging the adoption of sustainable practices through human actions to reduce energy consumption and environmental impacts.[34] By fostering individual and collective action towards more sustainable lifestyles, the LiFE Mission directly contributes to India's efforts to reduce energy consumption and achieve its net-zero climate goals.

The LiFE mission provides specific recommendations for energy-saving practices. Some of these relevant to the decarbonisation measures discussed in this report include purchasing 5-star rated appliances certified by the Bureau of Energy Efficiency (BEE), keeping electronic devices in energy-saving mode, use of smart switches for appliances, and keeping the temperature of air conditioners to 24°C.[35] These steps are designed to minimise unnecessary energy consumption and promote energy-efficient behaviours.



However, to scale the adoption of these behaviours requires a systems view of the barriers to change and an approach that utilises multiple behaviour change levers.

Barriers to Adoption of Energy-Efficient Behaviours

Despite advancements in energy-efficient technologies, awareness and knowledge gaps remain key barriers to widespread adoption in India's residential sector. Many homeowners are unaware of the energy consumption patterns of their households, with little understanding of how factors like equipment efficiency and building design impact energy usage. This lack of clear, accessible information about energy use limits informed decision-making.

Although developers often adopt green building standards and obtain green building certifications, they rarely communicate the benefits of energy-efficient design to potential buyers. These certifications focus on lowering energy use but offer little guidance on the actual energy consumption of individual apartments over time. Hence, energy efficiency is not a key driver during home purchases.

Furthermore, without market-driven demand for energy performance metrics, developers have little incentive to highlight the energy efficiency of their properties. This absence of competition on energy performance further reinforces a status quo where homebuyers do not prioritise energy efficiency.

By making consumers aware of expected energy performance standards, there is potential for a shift in behaviour toward reducing energy consumption. Once informed, homeowners could begin demanding performance data, comparing their real-world energy usage against estimated benchmarks. This could drive greater market demand for energy-efficient homes, creating a cycle where developers compete on energy performance, and consumers benefit from reduced energy costs.

Recommendations for Targeting Change in Consumer Behaviour and Choices

To effectively raise awareness surrounding energy-efficient practices and overcome the associated barriers, the Centre for Behaviour and Environment developed the *Levers of Behaviour Change* as the core framework for driving behavioural shifts in energy consumption within India's built environment.[36] This framework offers a direct, actionable approach to influencing consumer decisions and habits by leveraging behavioural science principles. The Levers of Behaviour Change framework identifies six critical strategies that can be applied to promote energy-efficient behaviours. Each lever focuses on a specific area that motivates people to adopt energy-efficient practices, ranging from providing clear information to enforcing regulatory measures. By focusing on these six levers, we can develop a comprehensive strategy, as shown below, that not only addresses information gaps but also considers social norms, financial gaps, and regulatory support, ensuring sustained behaviour change, influencing consumer decisions, and ultimately creating a culture of energy efficiency in the residential sector. To ensure the success of these interventions, a collaborative effort involving multiple stakeholders is essential.

Recommended Intervention 1:

Establish standardised energy performance ratings for residential buildings and deploy smart energy use dashboards/online home energy reports.

Intended Behavioural Change:

- Energy efficiency practices like 5-star fans, and 5-star RACs can become a norm in the residential sector by enforcing policies that mandate energy efficiency ratings for residential buildings.
- Energy performance of homes can be included in the decision-making of home buyers or renters by quantifying the performance through ratings that are easy to interpret.

Implementation of the Recommendation:

- Standardised energy performance ratings for the residential sector can be championed and implemented by regulatory bodies such as national or sub-national government agencies.
- Technology solution providers in collaboration with utility companies can help deploy the smart energy use dashboards or online home energy reports for ease of accessibility.
- Developers can help mainstream the use of energy performance ratings for potential home buyers/ renters by providing actionable information about energy consumption and efficiency benefits.

Recommended Intervention 2:

Implement a national awareness campaign and identify energy efficiency ambassadors at the national and sub-national level.

Intended Behavioural Change:

- Establishing a wide-reaching public awareness campaign can help create a national narrative around the importance of energy-efficient practices like cool roofs, 5-star fans, and 5-star RACs in homes.
- Energy-efficient behaviours can be mainstreamed by leveraging peer influence and community-driven or media-driven campaigns.

Implementation of Recommendation:

- NITI Aayog can help fund and manage the awareness campaign and collaborate with NGOs, media companies, and social platforms for implementation on a national scale.
- Educational institutions and community leaders can help champion the cause by being ambassadors of energy-efficient behaviours.

Recommended Intervention 3:

Introduce performance-based financial incentives for energy-efficient homes.

Intended Behavioural Change:

- Financial incentives can motivate developers to adopt and promote energy-efficient practices like cool roofs in the residential sector.
- Ensuring the affordability of 5-star fans and 5-star RACs through financial incentives can help make energy-efficient homes more accessible and attractive to low- and middle-income households.



Implementation of Recommendations:

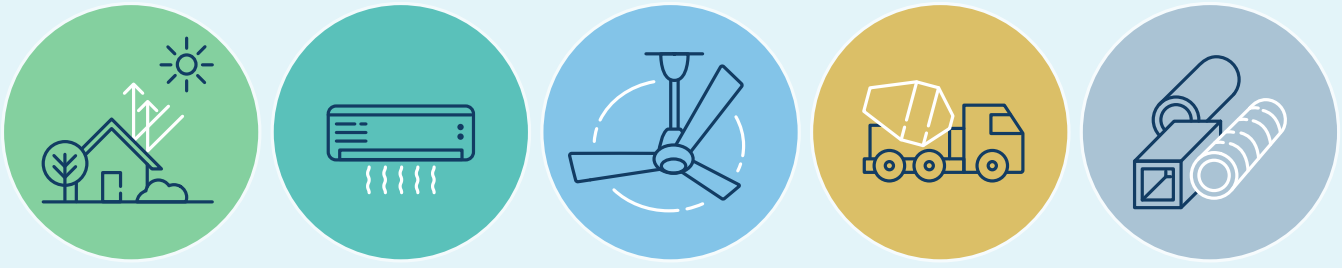
- By providing affordable loans and subsidies for energy-efficient retrofits and new constructions, government bodies and financial institutions can make it financially feasible for stakeholders to invest in sustainable practices.
- Financial incentives can help developers achieve compliance with energy performance standards and offer energy-efficient homes to potential buyers and renters.

Roadmap to Mainstream Net-Zero Carbon Buildings

India is on the cusp of a construction explosion to meet growing housing needs, especially in the urban residential sector. This rapid rate of urbanisation in India's cities provides an opportune moment to "build right the first time." That means avoiding lock-in effects of high energy use and carbon intensity due to business-as-usual construction practices. The convergence of growing urbanisation and the government's focus on providing housing for all, makes it a truly unique moment to enable the adoption of low-carbon construction and scale action at the city and national levels to decarbonise the urban residential sector.[37] MoEFCC's India cooling action plan lays out recommendations to mitigate the severe impacts of climate change on the built environment. Building on this framework, the following *Think-Do-Scale* framework is recommended, as explained in **Exhibit 20**. This framework looks at near-term, medium-term, and long-term actions that can be taken by central, state, and city governments; financing institutions; and construction industry stakeholders to mainstream net-zero carbon buildings in India.



Exhibit 20 **The Think-Do-Scale Framework to Mainstream Net-Zero Carbon Buildings**



Scale – Adoption of Codes, Standards and Scaling Mechanisms

Do – Piloting and Providing Financial Incentives

Think – Knowledge Sharing

AWARENESS CAMPAIGNS

Educate various stakeholders on the technical solutions through awareness campaigns and industry coalitions. This can also support the development of green procurement frameworks.

Timelines: Near term
Stakeholder: Government, building sector players

PILOTS AND FINANCIAL INCENTIVES

Pilots serve as proof points to reduce risk of adoption, ensuring the scalability of solutions. Appropriate financing mechanisms for adopting innovative technical solutions are essential for on-scale adoption by the building sector.

Timelines: Medium term
Stakeholder: Developers, financing institutions, and building sector players

IMPLEMENTING CODES AND STANDARDS

Implementation of model building bye-laws and updated codes that incorporate the performance requirements for projects. Adoption of behavioral change interventions and leveraging the national housing programme of Pradhan Mantri Awas Yojana (Urban) or PMAY(U).

Timelines: Long term
Stakeholder: Government

RMI Graphic. Source: RMI analysis.

Think: Knowledge Sharing and Awareness Campaigns

A multi-faceted approach involving various initiatives and stakeholders is essential to effectively design awareness campaigns and knowledge sharing. Here are some recommended actions:

Public Awareness Campaign: Launch comprehensive educational campaigns to underscore the importance of energy performance in home-buying decisions. Highlighting the financial benefits like reduced utility bills and increased property value can appeal to consumers' practical side, while stressing the environmental advantages can resonate with those motivated by sustainability.

Green Public Procurement (GPP) Frameworks: Develop GPP frameworks for scaling decarbonisation solutions by leveraging government purchasing power to drive demand for low-carbon products and services. They transform markets by prioritising sustainable options, mitigating financial risks for suppliers, and establishing clear standards for carbon reduction. Additionally, GPP stimulates economic growth by creating green jobs and aligns public spending with climate goals, significantly advancing decarbonisation efforts.

Community Energy Ambassadors: Identify and train community leaders, such as schoolteachers, local government officials, and community organisers, to serve as community energy ambassadors. These ambassadors will play a pivotal role in educating their communities by organising local workshops, facilitating peer learning initiatives, and utilising social media platforms.

Local Workshops and Peer Learning: Leveraging the influence of community energy ambassadors, organise local events and discussions to raise awareness of energy-efficient behaviours. These workshops will focus on sharing practical tips and demonstrating the tangible benefits of adopting energy-efficient practices within the community, fostering a culture of sustainability.

Nationwide Awareness Campaign: Roll out a nationwide campaign akin to NITI Aayog's Shoonya Campaign, utilising a variety of media platforms, including TV, radio, social media, and digital ads. This campaign should emphasise the financial, social, and environmental benefits of energy-efficient homes and behaviours, aiming to reach a broad audience and inspire widespread change.

Recognition Programmes: Establish a system of recognition and rewards to honour communities or buildings that show exceptional commitment to energy-efficient practices. These awards can serve as powerful motivators, encouraging others to follow suit and collectively reduce energy consumption.

Do: Piloting and providing financial incentives

Piloting the solutions and implementing financial incentives to promote decarbonisation in the building sector is crucial for accelerating the adoption of energy-efficient practices. Here's how such a strategy can be structured:

Pilot Projects: Pilot projects are essential for scaling energy-efficient solutions as they provide a controlled environment to test and refine new technologies such as the proposed decarbonisation interventions, reducing risks and costs associated with large-scale implementation. They generate valuable data and insights, proving the concept's effectiveness and engaging stakeholders, including regulatory bodies. Successful pilots offer concrete examples that help secure funding and support for

broader rollouts. Additionally, lessons learned can be adapted to different contexts, making it easier to scale solutions effectively and achieve sustainability goals.

Subsidies and Low-Interest Loans: By partnering with financial institutions, the government can offer homeowners affordable financing options for energy-efficient upgrades. These loans and subsidies should target retrofits such as cool roofs, enhanced insulation, and energy-efficient appliances. Lowering the financial barriers to these improvements will make it more feasible for homeowners to invest in sustainable technologies, resulting in significant energy savings and reduced carbon emissions.

Tax Incentives for Developers: Providing tax incentives to developers who construct energy-efficient homes that meet established energy performance standards is an effective way to encourage sustainable building practices. These incentives not only motivate developers to prioritise energy efficiency in their projects but also help elevate the overall standard of new constructions. By tying financial benefits to compliance with high-efficiency standards, we can drive meaningful improvements in the built environment.

Public–Private Partnerships: Strengthening the collaboration between government and private financial institutions is essential to ensure that financial incentives are widely available, particularly in underserved markets. Special programmes focused on low- and middle-income households will make energy-efficient homes and technologies more accessible to these segments. Through these partnerships, we can leverage resources and expertise to create inclusive financial programmes that support the widespread adoption of energy-efficient practices.

Performance-Based Incentives: Offering financial incentives for projects that meet specific energy and carbon performance thresholds, such as green building certifications, can further encourage sustainable practices. By setting clear performance goals and rewarding projects that achieve them, we create a results-driven approach to decarbonisation. This not only fosters a culture of excellence in energy efficiency but also ensures that the financial incentives are directly linked to measurable environmental benefits.

In sum, these financial incentives — subsidies and low-interest loans, tax incentives for developers, public-private partnerships, and performance-based rewards — can collectively drive significant progress in decarbonising the building sector. By lowering financial barriers and rewarding sustainable practices, we can accelerate the transition to a low-carbon future.

Scale: Adoption of High-Performance Building Solutions

Adopting long-term goals is essential to mainstream net-zero carbon buildings in India to accelerate adoption rates. Also, enforcing codes and standards at the sub-national government departments is essential. The following sections outline how this can be achieved:

Incorporate Requirements to Lower Embodied Carbon Emissions in Model Building Bye-laws and Rating Systems: As methodologies and databases for embodied carbon assessments mature, including these requirements in model building codes is feasible. Environmental Product Declarations play a crucial role by providing transparent and standardised information about the environmental impact of products throughout their lifecycle, which can guide the selection of low-carbon materials and practices.

Standardised Residential Energy Performance Thresholds: Building upon the residential building code (ENS), building sector stakeholders can collaborate with developers, the Bureau of Energy Efficiency, and green building rating agencies to set specific energy thresholds and limits for different types of homes within various climate zones. Like the BEE star rating system for appliances, these standardised thresholds will ensure that new residential buildings meet minimum energy performance standards.

Mandate Disclosure of Energy Performance: Developers and real estate agents should be legally required to disclose energy performance metrics, such as expected annual energy consumption, for all newly constructed homes during the sales process. This transparency helps homebuyers make informed decisions based on energy efficiency, driving demand for more sustainable homes.

Centralised Platform for Comparison: An online platform where potential homebuyers can easily compare the energy performance ratings of various residential properties will provide transparency and empower them with actionable information. This centralised platform will allow buyers to prioritise energy-efficient homes, fostering a market shift towards sustainability.

Smart Meters Installation: Collaborating with utility companies to install smart meters in residential homes will enable tracking of real-time energy usage. These meters will feed data into a dashboard accessible via a mobile app or web portal, providing households with insights into their energy consumption patterns.

Energy Dashboards and Reports: Developing user-friendly energy dashboards that provide real-time data on daily, weekly, and monthly energy consumption; comparisons with similar homes; personalised energy-saving tips; and detailed home energy reports will empower individual households to monitor and improve their energy efficiency.

Community-Level Energy Dashboards: Introducing community dashboards that track the collective energy consumption of neighbourhoods or residential societies can encourage communities to set and achieve energy-saving goals. This collective effort contributes to the larger goal of energy efficiency.

Update PMAY(U) Programme Deployment: By ensuring environmental clearances for projects to include quantifying and reporting estimated annual operational and embodied carbon emissions, we can leverage the Pradhan Mantri Awas Yojana (Urban) programme to promote sustainability. Providing simpler, easy-to-use input forms by the central ministry will facilitate project-level reporting and compliance.

By implementing codes and standards, while incentivising energy-efficient choices, India can effectively mainstream net-zero carbon buildings, contributing significantly to the country's climate goals and setting a global precedent for sustainable development.

Comprehensive Policy Recommendations to Enhance Adoption Within India's Built Environment

Scaling Up Cool Roofs in the Country

- **Quantify the Potential of Cool Roofs in Cities**
  Conduct a comprehensive assessment to estimate the potential for cool roof adoption across various Indian cities. Consider parameters such as solar radiation, roof area availability, building typology, and urban heat island effect intensity. Identify target areas and quantify the benefits in terms of energy savings, cooling load reduction, and peak electricity demand mitigation.

- **Define a Phased Approach for Cool Roof Implementation — Prioritise Building Types and Land Use**
  A phased approach to cool roof adoption will ensure effective resource management for city-wide deployment. The initial phase should prioritise heat mapping to identify heat-stressed areas and high-impact building types, such as affordable homes for vulnerable populations. Next, institutional buildings like schools and universities should be targeted. Finally, focus on warehouses and industrial buildings, which experience significant heat gain and would benefit from energy savings.



- **Develop Guidelines for Cool Roof Implementation**
  Develop cool roof implementation guidelines to share information on various materials and standardise specifications like solar reflectance, thermal emittance, and material durability. This can include deployment techniques and maintenance protocols. Focus on urban planning aspects, identifying neighbourhoods or zones for cool roof implementation.

- **Implement Pilot Projects to Demonstrate the Impact of Cool Roofs on Different Building Typologies**
  The pilots should include high-rise affordable housing, institutional buildings, and industrial warehouses to validate cool roof performance across diverse building types. Testing various materials under different conditions will prove their effectiveness in reducing heat gain, improving thermal comfort, and achieving energy savings. This demonstration will build a robust evidence base for scaling cool roof solutions across the country.

- **Integrate Cool Roofs in the City and State bye-laws**
  State bye-laws are regulations set by state governments to control building construction, safety, and land use. They cover aspects like building height, setbacks, materials, and environmental standards, ensuring that construction aligns with safety and development norms. Amending city and state building codes and bye-laws to mandate or incentivise the use of cool roofs, particularly in new construction and retrofitting projects, can ensure widespread adoption and consistent implementation.

- **Integrate Cool Roofs in Schedule of Rates (SOR)**
  The SOR is a government-issued document listing standardised rates for construction materials, labour, and equipment primarily used in public projects. Integrating cool roofs in the Public Works Department (PWD) Schedule of Rates will standardise pricing for cool roof installations across government projects, making it easier to budget and plan for cool roof adoption.

- **Cool Roofs in Pradhan Mantri Awas Yojana (PMAY) and State Housing Schemes**
  Integrating cool roofs into Pradhan Mantri Awas Yojana (PMAY) projects will enhance thermal comfort for low-income households while building confidence among national and state-level stakeholders to adopt this solution widely. Similarly, incorporating cool roofs in state housing schemes can serve as a scalable model for improving living conditions and promoting sustainable construction practices across India.

- **Develop Training and Capacity Building Programmes for Building Trade Workers**
  Developing training programmes for architects, engineers, contractors, and construction workers on cool roof installation and maintenance will ensure quality implementation and long-term performance. Training should cover material selection, installation techniques, safety practices, maintenance requirements, environmental benefits, and energy savings. Roll out these programmes through local vocational centres, industry associations, and educational institutions to create a skilled workforce for expanded cool roof adoption.

Increasing Penetration of Energy-Efficient Fans in India's Residential Sector

- **Establish Direct Interlinkage Between Industry and Demand Aggregators**
    - Facilitate direct engagement between industry (e.g., fan manufacturers) with aggregators like EESL to leverage economies of scale and secure competitive pricing for energy-efficient fans at the developer level. This focuses on the broader benefits of direct engagement, such as improved pricing and access to a wider range of products.[38]
    - Explore collaborative initiatives with industry players, including volume-based purchasing agreements with real estate developers with access to subsidised or discounted energy-efficient fans if they are installed before occupancy certificates are provided by the local regulatory bodies.[39]

- **Increase the Minimum Energy Performance Standard for Fans**
  Gradually increasing Minimum Energy Performance Standards (MEPS) for fans and phasing out less efficient options over time incentivises manufacturers to develop more efficient models, promoting innovation. This phased approach, along with a clear roadmap and regular reviews, encourages manufacturers to invest in research and development while providing consumers with access to increasingly energy-efficient and cost-effective fans, ultimately benefiting both the environment and consumers.[40]

Increasing Penetration of Super-Efficient ACs in India's Residential Sector

India's room air conditioner market has significantly evolved over the past 10 years from fixed-speed AC to predominantly inverter AC today. Although the minimum energy performance standard has improved incrementally to eliminate the worst-performing products and bring higher-efficiency products to market, a gap remains between the performance levels of a 5-star AC and a super-efficient AC, as demonstrated through the work undertaken by the Global Cooling Efficiency Accelerator. Policy and market mechanisms that support the commercialisation of super-efficient ACs by the industry will help make them a market reality. Below, we list our recommendations to mainstream this technology:

- **Short-Term Policy Guidance**
  Undertake pilot projects to demonstrate, at scale, the superior performance and emission benefits of deploying super-efficient room ACs at a building level compared to the incumbent products (3-star and 5-star) sold in the India market today. Such performance validation and data will build buyer confidence and catalyse demand of super-efficient ACs from large buyers and will help spur the production of such ACs in India by progressive manufacturers.

  Update the performance metrics such as ISEER that characterise room air conditioners to better align with real-world performance, including dehumidification. Updating the current performance metric used to rate the performance of air conditioners to one that considers the energy impact of achieving desired humidity conditions will ensure manufacturers are designing for the right target. This change will also help consumers differentiate between cooling products that provide humidity control and those that do not.

- **Medium-Term Policy Recommendations**
  Integrate the purchase of super-efficient ACs in public procurement frameworks for all public buildings at the national and state levels. Government and public institutions are typically responsible for owning and operating the air conditioners and, as a result, would benefit from the significantly lower lifecycle cost of super-efficient air conditioners. Additionally, using super-efficient ACs will dramatically reduce the peak demand and consequently reduce the stress on electricity grids, as well as avoid millions of dollars of investment in grid infrastructure, allowing those funds to be used towards supporting national development and social priorities.

- **Long-Term Recommendations: Create an Ecosystem for Manufacturing and Supply**
  Provide financial and regulatory assistance to original equipment manufacturers to support knowledge transfer and develop supply chain and production capacity. Through production-linked incentive schemes and regulatory support, the central government can incentivise research and development of high-efficiency heat exchangers, compressors, and controls critical to the development and commercialisation of super-efficient ACs in India.

Cement and Concrete Decarbonisation

Approximately 40% of the emissions from cement production are generated by burning fossil fuels to heat kilns to the high temperatures required for the calcination process, which produces clinker — a key intermediate in cement manufacturing. Within this process, around 50%–60% of the CO_2 emissions result from a chemical reaction (calcination) during clinker production. Strategies to optimise and reduce the quantity of concrete, using clinker-free alternatives to cement, and introducing supplementary cementitious materials (SCMs) such as fly ash and slag in the concrete mix will significantly reduce carbon emissions.[41]

- **Improve Manufacturing Efficiency and Market Connectivity in the Short Term**
  To reduce emissions from process heat, retrofit existing kilns with efficiency upgrades and embrace a circular economy. Increase the collection, segregation, and usage of construction and demolition waste and optimise concrete mixes and constituents. Additionally, reduce emissions from process heat by using alternative fuels such as rice husk, coffee husk, nut shells, tyre chips, rubber dust, pet coke, coal dust, processed municipal solid waste, pharmaceutical waste, excess grease and lubricating oil, sawdust, and animal waste.[42] Enhance connectivity between SCMs and concrete manufacturers and reevaluate existing prescriptive specifications on SCM content limitations in codes and standards with performance-oriented specifications. Facilitate transportation, improve the availability of quality SCMs, and strengthen their connection with cement manufacturers.[43]

- **Pilot and Test Low-Carbon Cement Alternatives in the Medium Term**
  Use SCMs from non-fossil fuel sources like glass pozzolan and rice husk. Test high concentrations of SCM in concrete and clinker substitutes. Address safety concerns around the strength of blended products through real-time validation and on-site monitoring with affordable, off-the-shelf sensors. Recycle concrete for aggregate.[44]

- **Invest in Research and Development of New Kiln Technologies For Long-Term Solutions**
  The central government, through production-linked incentive schemes, can incentivise research and development of indigenous technologies. This includes new kiln technology that uses alternative fuels for heating during clinker production for ordinary Portland cement. Another solution with good potential is to make concrete a net carbon sink through CO_2-injected cement products and CO_2-sequestered curing or aggregates.[45]

- **Integrate Low-Carbon Cement in Schedule of Rates**
  Integrating low-carbon cement in the Public Works Department (PWD) Schedule of Rates will standardise pricing for low-carbon cement across government projects, making it easier to budget and plan for adoption.

- **Use Different Grades and Mixes of Concrete for Different Applications and Typologies**
  Utilising different grades and mixes of concrete tailored to the specific strength requirements of both sub-grade and super-grade structures ensures efficient and optimal material usage. This approach allows for the selection of the most suitable concrete for each application, preventing over-design and minimising material waste.

- **Conduct Research and Development of the Impact of Different Aggregates and Impact of Water Chemistry on Concrete Mix**
  Different aggregates, such as crushed stone, gravel, and recycled materials, present unique physical and chemical properties that significantly impact the strength, durability, and workability of the concrete and are also subject to regional availability. Furthermore, the chemical composition of the mixing water, encompassing factors beyond hardness, such as pH, dissolved salts, and impurities, plays a crucial role in the hydration process, strength development, and long-term durability of the concrete.

- **Monitor Concrete Curing and Setting Behaviour Utilising Advanced Sensor Technologies**
  Embedded sensors with wireless communication capabilities allow real-time monitoring of concrete temperature, humidity, and strength development. This data-driven approach enables proactive management of curing conditions, ensuring adherence to specified requirements and mitigating the risk of potential defects.

Steel Decarbonisation

- **Near-term Policy Interventions and Recommended Actions**
  Some short-term policy recommendations to decarbonise production and stimulate a market for low-carbon steel in India are detailed below.

- **Incentivise International Collaboration and Knowledge Sharing**

  - **Global Steel Circularity Knowledge Hub:** Establish a centralised platform and foster cross-border research partnerships to facilitate the exchange of best practices and research to accelerate innovation in steel circularity. These collaborations should focus on sharing resources, expertise, and infrastructure to achieve breakthrough developments.[46]

  - **Pilots and joint demonstration projects:** Demonstrate pilot programmes that evaluate innovative circular practices and recycling technologies in collaboration with industry, academia, and government. These projects should provide comprehensive data on technical feasibility, economic viability, and environmental impact to guide future policy and investment.[47]

- **Create a Robust Market for Low-Carbon Steel**

  - **Regional scrap exchange platforms:** Develop regional scrap steel exchange platforms to improve access to secondary materials. These platforms would enhance the efficiency of scrap metal distribution and reduce trade barriers, ultimately lowering the costs of recycled steel and supporting circular supply chains across borders.[48]

  - **Integrated standards:** Harmonise standards across trading partners to reduce technical barriers to trade, including reporting frameworks, impact assessment methodologies, material tracking, quality assurance, and environmental performance. This will ensure consistent and safe material specifications for recycled steel, build confidence in recycled materials, and enable their seamless integration into production processes.[49]



- **Market development programmes:** Implement programmes to stimulate market demand for recycled steel products, including awareness campaigns and demonstration projects showcasing successful applications.

- **Provide Financial Assistance to Stimulate Demand**

  - **Infrastructure investment fund for steel recycling:** Support the development and expansion of state-of-the-art steel recycling facilities. This fund could finance investments in modern recycling plants, recovery technologies, and logistics to support the transition, improve the efficiency of steel recycling, and reduce over-reliance on primary steel production.[50]

  - **Provision of subsidies and grants to micro, small, and medium (MSME) steel producers:** Offer targeted grants and subsidies to support MSME steel producers, particularly those using the induction furnace route, which maximises scrap usage in production. This assistance would help smaller enterprises overcome financial barriers and accelerate the adoption of sustainable practices.[51]

  - **Tax credits for recycled steel use:** Offer tax credits to incentivise projects and businesses that incorporate a significant amount of recycled steel, driving demand and enhancing market pull for circular steel products.

  - **Low-interest loans and grants to developers:** Provide low-interest loans and grants to support the green premium paid for uptake of low-carbon steel by the private sector.

- **Standardise Construction Waste Management Across the Country**

  - **Digital material passport system:** Implement a digital material passport system that records and tracks materials from construction to end-of-life. This digital tracking would enable efficient sorting and reuse of materials, thereby minimising waste and promoting steel reuse.[52]

  - **Mandatory pre-demolition audits:** Establish mandatory audits prior to demolition to assess recoverable materials and maximise the reclamation of steel and other reusable components. This practice would enhance the recycling rate and reduce landfill waste.[53]

  - **Promotion of buy-back programmes:** Encourage contractors and manufacturers to implement buy-back programmes for steel products, thereby enabling easy return of materials for recycling by homeowners and developers and facilitating reprocessing of steel into the supply chain to promote circularity in the construction sector.

- **Invest in Research and Development Initiatives**

  - **Recycling technology innovation:** Invest in R&D for advanced recycling technologies to enhance the quality and yield of recycled steel, with a focus on energy-efficient, low-emission processes.[54]

  - **Quality assessment methods:** Support the development of standardised quality assessment methods for recycled steel, ensuring consistent quality across supply chains.[55]

- **Long-Term Strategic Interventions Using Government Regulations**

Once the market alternatives have been established, the central and state governments can simultaneously take the following steps to mandate the use of low-carbon steel through various regulatory initiatives.

  - **Minimum recovery rate requirement:** Introduce a minimum recovery rate for steel producers, starting with achievable baseline rates and increasing over time. These sector-specific targets should consider technological capabilities to ensure a significant portion of end-of-life steel re-enters the supply chain. This will enhance resource efficiency, promote recycling, encourage circular supply chains, and optimise material flows through collaboration among steel producers, recyclers, and end-users.[56]

  - **Minimum recycled content in construction:** Introduce minimum recycled content requirements for steel products in construction projects, with sector-specific targets that increase over time. Base these requirements on technical feasibility and market readiness, including specific requirements for different steel products and applications. This will drive demand for circular materials and reduce the building sector's carbon footprint.[57]

  - **Green procurement standards:** Develop of comprehensive guidelines in central and state government procurement policies for preferential purchase of recycled steel, reinforcing market demand for circular steel products and making them an essential part of any sustainable purchasing strategy.[58]

  - **End-of-life standards:** Establish standards for the proper dismantling and recycling of steel components from end-of-life projects, minimising waste and maximising recovery rates.

Appendices

Appendix A: Defining a Net-Zero Carbon Building

A comprehensive literature review was conducted to analyse existing definitions of net-zero carbon buildings in the United States, Europe, and India. This review synthesised a wide range of sources, including academic research, policy documents, industry standards, and case studies. The findings from this review, along with the existing body of work in India, informed the development of a tailored definition for net-zero carbon buildings in the Indian context:

A net-zero carbon building is one that employs a comprehensive strategy to minimise greenhouse gas emissions associated with its operational energy use within the overall building site limits. This involves reducing energy consumption through efficient design and technologies. Any remaining emissions are then balanced or offset, either on- site or off-site, to achieve a net- zero carbon footprint.

Criteria for a Net-Zero Carbon Building

If a building is to be defined as a net-zero Carbon building, it must meet all the three criteria detailed below.

- The annualised net GHG emissions of the building shall be equal to or less than zero (0)
- The GHG emissions are accounted for a defined period of one year
- Net GHG emissions annually shall be calculated using Equation below

Equation

$$G_{net} = [(E_{imp} \times G_{imp}) + (E_{ren} \times G_{ren}) + (E_{nren} \times G_{nren}) + (R_{leak} \times G_{leak})] - [(E_{rec} \times G_{rec}) + (E_{exp} \times G_{exp})]$$

Definition of terms used in equation (1).

G_{net} = Net greenhouse gas emissions for the site

E_{imp} = off-site energy imported into the site boundary (renewable + non-renewable)

G_{imp} = greenhouse gas emission factor for imported energy

E_{ren} = on-site energy generated through renewable energy

G_{ren} = greenhouse gas emission factor for on-site generated renewable energy

E_{nren} = on-site generated non-renewable energy

G_{nren} = greenhouse gas emission factor for on-site generated non-renewable energy

R_{leak} = refrigerant leakage calculated annually for the air-conditioning systems

G_{leak} = greenhouse gas emission factor for the calculated refrigerant leakage

E_{rec} = off-site renewable energy using renewable energy certificates or power purchase agreements

G_{rec} = greenhouse gas emission factor for off-site renewable energy using renewable energy certificates or power purchase agreements

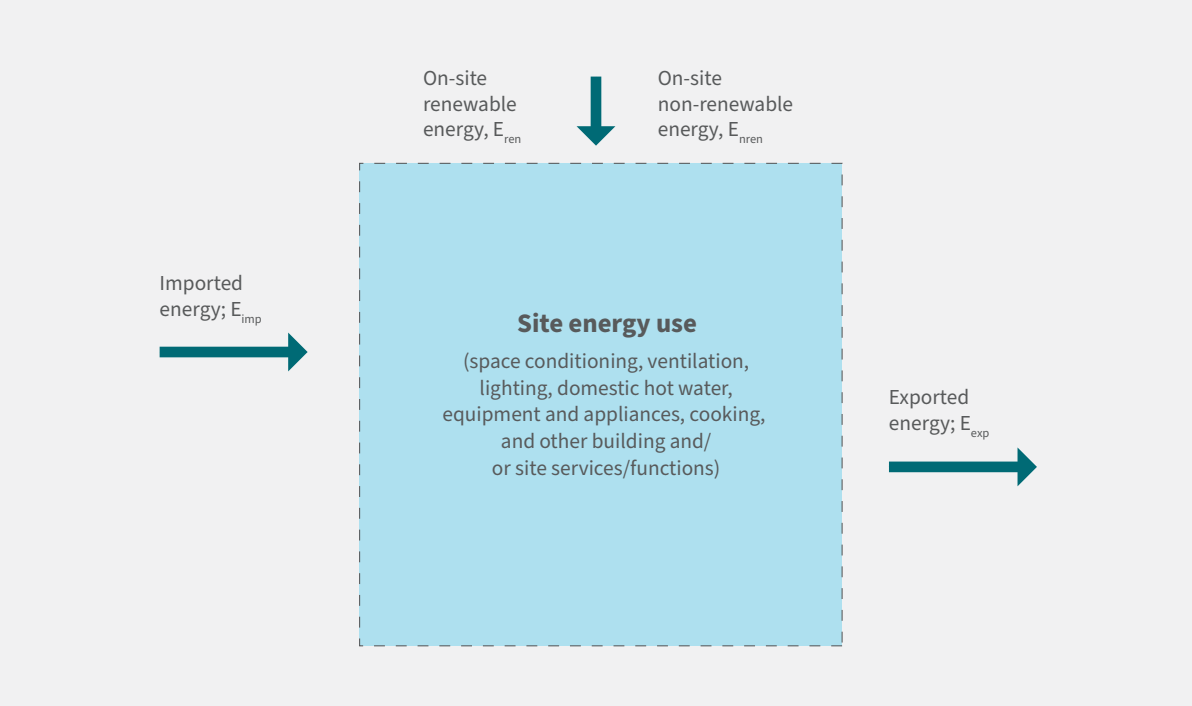
E_{exp} = excess energy generated (renewable + non-renewable) exported out of the site boundary

G_{exp} = greenhouse gas emission factor for exported energy

System Boundary

Exhibit 6

System Boundaries for the Proposed Definition of "Net- Zero Carbon Building"



RMI Graphic. Source: RMI analysis.

Imported Energy

- E_{imp} = Net energy imported to the site
- E_{del} = off-site energy imported into the site boundary (renewable + non-renewable) for the building operation and supporting services

- E_s = energy used for maintenance for the site area apart from the building operational energy
- Net imported energy is calculated as: Eimp = Edel + Es

On-site Energy Generation

- E_{ren} = on-site generated renewable energy utilised for the site
- E_{nren} = on-site generated non-renewable energy utilised for the site

Exported Energy

- E_{exp} = Net on-site generated excess energy (renewable + non-renewable) exported out of the site boundary

Appendix B: Modelling Assumptions

The goal of the techno-economic analysis is to estimate the national and sectoral level costs and benefits of implementing a series of emissions reduction interventions in new construction from now until 2050. By analysing these interventions, the model aims to provide a comprehensive understanding of the potential financial investments required and the environmental benefits that can be achieved. The model estimates the energy and emissions reductions as well as the cost premium associated with the proposed 5 high-impact building decarbonisation measures. Energy and emissions calculations are performed on a per-square-meter basis (i.e., energy and emissions reductions are estimated per square meter of floor area). These values are then scaled to the building stock based on the projected countrywide building floor area in the LBNL model. Below are some key assumptions related to the techno-economic analysis of the proposed building decarbonisation measures:

Cool Roofs

1. The use of cool roofs results in a 14% energy consumption reduction associated with cooling over business-as-usual construction.[59]
2. A cost learning rate of 1% is assumed for the cool roof technology.
3. The baseline penetration of cool roof technology is assumed to be 5% in the year 2025, linearly ramping up to 100% penetration by 2035.[60]

5-Star Fans

1. High-efficiency 5-star fans are, on average, 44% more energy efficient than traditional ceiling fans.[61]
2. A cost learning rate of 1% is assumed for 5-star fan technology.
3. The baseline penetration of 5-star fans is assumed to be 0.5% in the year 2025, linearly ramping up to 100% penetration in the year 2035.

Super-Efficient RACs

1. Super-efficient RACs are assumed to have an energy reduction of 59% over traditional room air conditioners.[62]

2. A cost learning rate of 1% is assumed for super-efficient RACs technology.

3. Baseline penetration of super-efficient RACs is assumed to be 0% in the year 2025 linearly ramping up to 100% by 2030. Based on 10-year lifetime of traditional air conditioners, all RACs are assumed to be replaced by super-efficient RACs at the end of their lifetime.

Low-Carbon Cement

1. Cement usage was modelled in three categories: existing business-as-usual, moderate commitment (moderately reduced emissions from measures like additives), and ambitious commitment cement (deeper reduced emissions from technologies like LC3 cement). We assume that the moderate commitment cement will grow exponentially until 2032. From 2032 to 2043, we assume that the ambitious commitment cement grows also grows exponentially in penetration.

Low-Carbon Steel

1. Steel manufactured using the blast furnace - basic oxygen furnace (BF–BOF) is assumed to be conventional baseline steel. Steel manufactured using less carbon-intensive processes, such as direct reduced iron-electric arc furnaces (DRI-EAF) fuelled by natural gas and green hydrogen, as well as steel manufactured from scrap, are assumed to be low-carbon steel alternatives.

2. In the baseline scenario, we assume that today's fraction of primary steel production types remains the same over the next 25 years (majority BF-BOF with some DRI-EAF steel powered by coal and natural gas).

3. In the green steel scenario, the percentage of green steel penetration in primary steel production grows over time in two time periods. First, the penetration of EAF using natural gas grows as a greener alternative to BF–BOF steel to 30% until 2035. Green steel penetration grows linearly from 0% in 2030 to 100% in 2050.

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