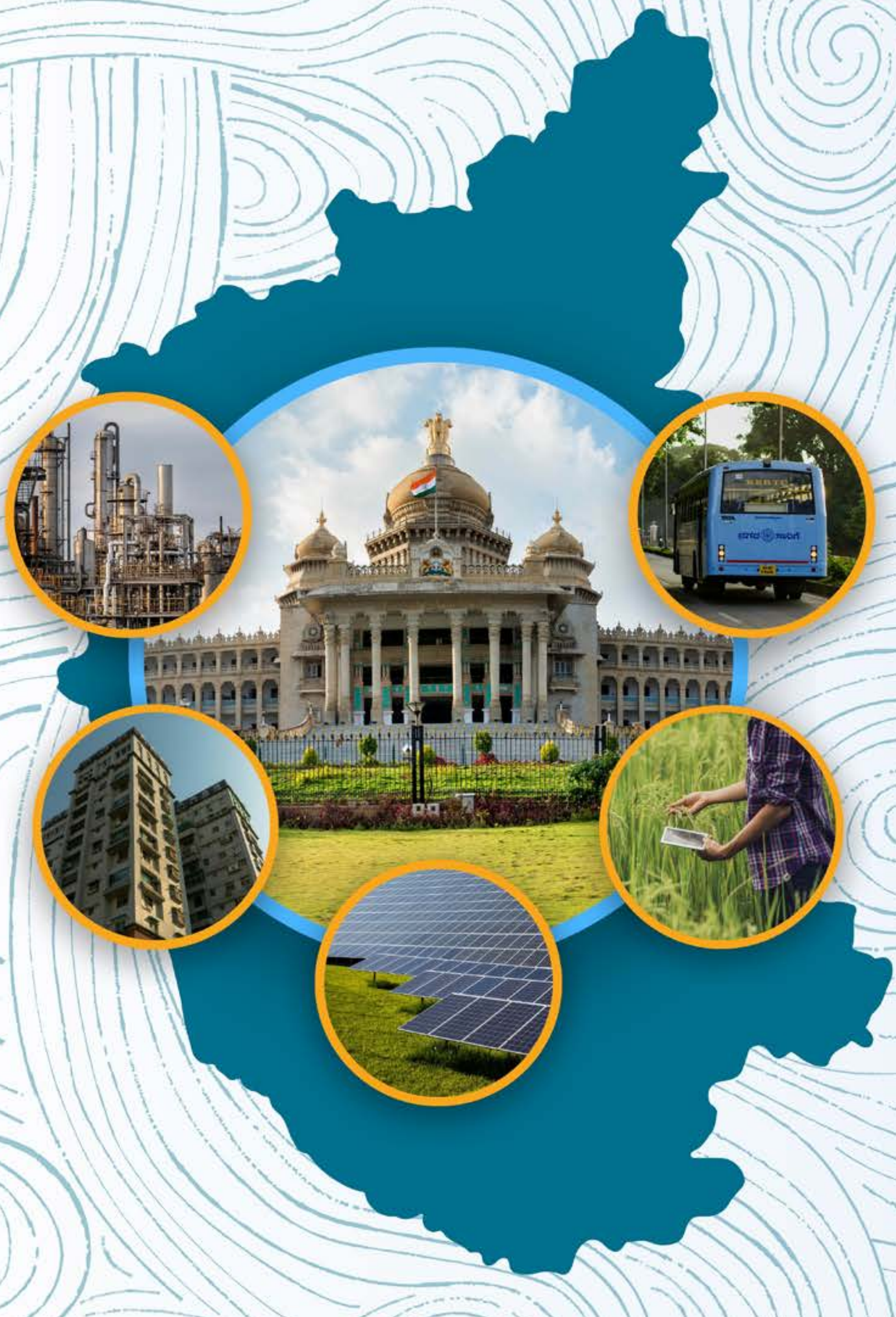
CSTEP

Namma SAFARI: Low-Carbon Development Pathways for Karnataka



Namma SAFARI: Low-Carbon Development Pathways for Karnataka

Kaveri Ashok | Ramya Natarajan | Anasuya Gangopadhyay | Divya Davis
Aparna Sundaresan | Sarah Khan | Chandrakiran L
Kunal Jagdale | Nandita Saraf | Upasna Ranjan
Krithika Ravishankar | Indu K Murthy

Center for Study of Science, Technology and Policy (CSTEP)

July 2025

Edited and Designed by CSTEP

Disclaimer

Suggested citation: CSTEP. 2025. *Namma SAFARI: Low-carbon development pathways for Karnataka*. (CSTEP-RR-2025-08).

July 2025

Editor: Shayantani Chatterjee

Designer: Alok Kumar Saha

Bengaluru

No. 18, 10th Cross, Mayura Street

Papanna Layout, Nagashettyhalli

RMV Stage 2, Bengaluru 560094

Karnataka (India)

Tel.: +91 (80) 6690 2500

Email: cpe@cstep.in

Noida

1st Floor, Tower-A

Smartworks Corporate Park

Sector 125, Noida 201303

Uttar Pradesh (India)

Acknowledgements

We extend our gratitude to Dr Shalini Rajneesh, IAS, Chief Secretary, Government of Karnataka, and Ms Uma Mahadevan, Additional Chief Secretary and Development Commissioner, Government of Karnataka, for enabling the consultations with line departments and for their valuable inputs throughout the project. We thank the International Sustainable Energy Foundation for supporting this project.

We would also like to express our sincere appreciation to Dr S S Krishnan (Advisor, CSTEP), Ms Rishu Garg (Senior Policy Specialist, CSTEP), and Ms Spurthi Ravuri (Research Scientist, CSTEP) for their input on the report and analysis. We would also like to thank all stakeholders from the Government of Karnataka, who took the time to share their valuable insights on our study: Dr Selvakumar, IAS, Principal Secretary, Commerce and Industries Department, Public Works Department; Ramesh R, Director (Technical Cell), Commerce and Industries Department; Dr N V Prasad, IAS, Secretary to the Government, Transport Department; Gajendra Kumar, Chief Mechanical Engineer, Bangalore Metropolitan Transport Corporation; K S Chaithra, Deputy Chief Mechanical Engineer, Bangalore Metropolitan Transport Corporation; Vijay Mohan Raj, IFS, Principal Secretary (Ecology and Environment), Forest, Environment and Ecology Department; Kavitha S Mannikeri, IAS, Housing Commissioner, Karnataka Housing Board; K P Rudrappaiah, Managing Director, Karnataka Renewable Energy Development Limited; Jagadeesh L Belagali, General Manager - Technical, Karnataka Renewable Energy Development Limited; D Kodandapani, Director (Technical), Department of Energy; Dr Paramesha K, Additional Director (Technical Monitoring), Department of Energy; Vinayak G Bhat, Joint Director (Projects), Department of Energy; D Padmavathi, Additional Director, Department of Energy; Naveen Raj Singh, IAS, Principal Secretary, Housing Department; Pankaj Kumar Pandey, IAS, Managing Director, Karnataka Power Transmission Corporation Limited; Chetan D, Chief Engineer (Electricity) – Planning and Co-ordination, Karnataka Power Transmission Corporation Limited; Vishwanath, Superintending Engineer (Electricity) – Planning and Co-ordination, Karnataka Power Transmission Corporation Limited; Dr Rashmi Alias, Joint Director of Agriculture (Seeds & State Farms), Department of Agriculture, Government of Karnataka, Bengaluru; Dasa Shiva Rama Krishna, Accredited Energy Auditor, KREDL/FICCI/PAT Cell; Sanjeev Maraddi, Chief Engineer, Rajiv Gandhi Housing Corporation Limited; Chandrashekar Gudi, Director, Directorate of Economics and Statistics; and Narasimha Phani, Joint Director - SIP Division, Directorate of Economics and Statistics.

We would also like to thank the following individuals and organisations from the private sector for their valuable contributions to this study: Suresh Patil, Head – Ready Mix Concrete and Key Accounts, UltraTech Cements; Kaustubh Phadke, General Manager and Country Head, Global Cement and Concrete Association – India; Prabodha Acharya, Chief Sustainability Officer, JSW Group; Radhika Dhall, Director, Confederation of Indian Industry – Karnataka; Shiny Samuel, Counsellor – GreenCo and Environmental Services, Confederation of Indian Industry – Karnataka; and Sameer Maithel, Founder Director, Greentech Knowledge Solutions Private Limited.

We are incredibly thankful to Dr Indu K Murthy (Sector Head, Climate, Environment and Sustainability, CSTEP) and Dr Jai Asundi (Executive Director, CSTEP) for their unwavering support and invaluable guidance throughout this project.

We also express our sincere thanks to the Communication and Policy Engagement team at CSTEP for their indispensable support in bringing this report to completion. We are particularly grateful to Shayantani Chatterjee for her meticulous edits and to Devashish Shukla and Alok Kumar Saha for their creative graphic design work.

ಸರ್ಕಾರದ ಪ್ರಧಾನ ಕಾರ್ಯದರ್ಶಿ (ಅರಣ್ಯ),
ಅರಣ್ಯ, ಜೀವಿಪರಿಸ್ಥಿತಿ ಮತ್ತು ಪರಿಸರ ಇಲಾಖೆ.

ಕರ್ನಾಟಕ ಸರ್ಕಾರ
Government of Karnataka

Principal Secretary to Government
(Forest),
Forest, Ecology and Environment
Department.

Low-Carbon Development Pathways for Karnataka, *Namma* SAFARI from CSTEP

The imperative for climate action is well-recognized, not only as a means to mitigate climate change but also to enhance resilience and safeguard natural resources from unsustainable exploitation. Developing a comprehensive roadmap toward a low carbon sustainable future necessitates a thorough understanding of projected growth across various sectors, and more importantly, the interdependencies and dynamic co-evolution of various sectors.

To support such strategic planning, several global models have been developed, typically employing Integrated Assessment Models (IAMs). However, these global models often underrepresent the perspectives and realities of the Global South. While a limited number of India-specific models exist, the **Sustainable Alternative Futures for India (SAFARI)** model, developed by the **Centre for Study of Science, Technology and Policy (CSTEP)**, is notable as the indigenous, system dynamics-based IAM designed at the national level and applied to a specific state context.

Also, **Namma SAFARI,** the system dynamics-based model to inform the design of low-carbon development pathways has been created first time for Karnataka. The model has been developed with careful consideration of the State's unique developmental priorities and resource constraints. It encompasses five key demand sectors—buildings, transport, industry, agriculture, forestry and land-use change—as well as the power supply sector.

While Namma SAFARI is grounded in rigorous mathematical modelling, a more accessible, user-oriented dashboard has also been developed to facilitate scenario analysis. For each sector, the dashboard provides a dedicated results page along with a set of adjustable levers to enable users to explore alternative policy and investment scenarios.

The efforts undertaken by CSTEP in developing both the model and the accompanying dashboard are commendable. These tools provide policymakers and other stakeholders with critical insights to support the formulation of robust, evidence-based strategies for achieving a low-carbon and sustainable future for Karnataka.

Dated: 29.05.2025

(PRABHASH CHANDRA RAY)

ಕೊಠಡಿ ಸಂಖ್ಯೆ: 442, 4ನೇ ಮಹಡಿ, ಗೇಟ್ ನಂ. 2, ಬಹುಮಹಡಿ ಕಟ್ಟಡ, ಡಾ॥ ಬಿ.ಆರ್. ಅಂಬೇಡ್ಕರ್ ವೀಧಿ, ಬೆಂಗಳೂರು – 560001
ದೂರವಾಣಿ: 080–2225 4434 / 2203 2570 ಮಿಂಚಂಚೆ: secyforest-fee@karnataka.gov.in
No. 442, 4th Floor, Gate No. 2, M.S. Building, Dr. B.R. Ambedkar Veedhi, Bengaluru - 560001
Tel: 080-2225 4434 / 2203 2570 E-mail: secyforest-fee@karnataka.gov.in

Executive Summary

The need for climate action is well established, not only to mitigate climate change but also to build resilience and prevent the depletion of resources due to overexploitation. Creating a roadmap towards a sustainable future requires a deep understanding of how each sector is expected to grow, and more importantly, how different sectors would interact with each other to co-evolve dynamically. Several models at the global scale and a few at the Indian scale have been created to facilitate this understanding. The Sustainable Alternative Futures for India (SAFARI) model developed by the Center for Study of Science, Technology and Policy (CSTEP) is one such example. However, to the best of our knowledge, there are no integrated long-term models for the state of Karnataka.

Namma **SAFARI is Karnataka's first integrated system dynamics model that maps how key sectors, such as energy, transport, industry, buildings, agriculture, and land use, interact and evolve up to 2050.**

To fill this gap, we developed a system dynamics model—*Namma* SAFARI—for Karnataka, wherein all key sectors of the economy are modelled up to the year 2050. The model structure, including growth drivers and all sectors considered, is shown in Figure ES1. The initial values used in the model were calibrated with appropriate government datasets. Karnataka's population, one of the main growth drivers in the model, was assumed to increase to a little over 75 million by 2050 (~10% increase from the current value). The other key growth driver is the Gross State Domestic Product (GSDP), which was estimated using a shift-share analysis. Karnataka's GSDP is projected to increase to INR 128 lakh crore by 2050 (2011 constant prices). Development goals such as affordable housing for all, thermal comfort, food security, energy for all, and healthcare and education for all also drive growth in different sectors, as described in detail in the report. Based on these growth drivers, the model estimated the electricity and fuel demands from each sector—buildings, transport, industry, and agriculture—in a bottom-up manner. The power sector is designed to meet all demands using a least-cost algorithm. Greenhouse gas emissions were then calculated based on the consumption of fuels and electricity generation mix. The land-use dynamics were also modelled to understand the land constraints as well as the agriculture, forestry, and land-use (AFOLU) emissions and sequestration in the state.

Through various impactful policies, Karnataka has gained sufficient momentum to be at the forefront of achieving India's long-term vision of net zero by 2070. Leveraging this advantage, announcing a concrete carbon-neutrality target for the state has several co-benefits such as attracting more investments, energy security, and job creation on the economic front and environmental aspects covering improved air quality, enhanced climate resilience of the state, and natural resource conservation.

– Prof Rajiv Gowda, Ex-Vice Chairman,
State Institute for Transformation of Karnataka

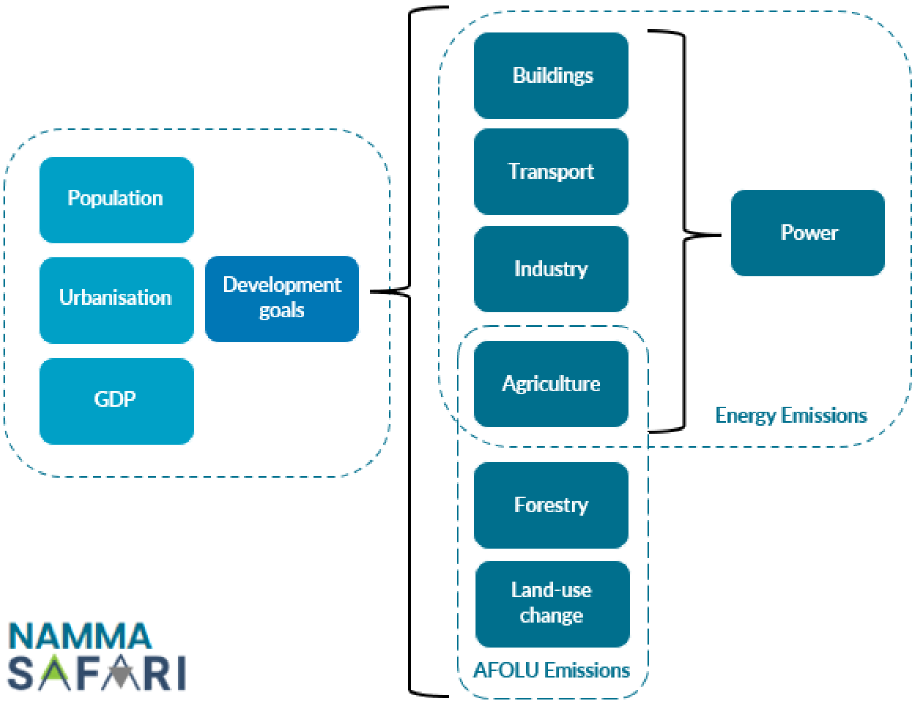


Figure ES1: Namma SAFARI model structure

While *Namma* SAFARI is a detailed mathematical model, a more accessible user interface dashboard was developed to help in scenario creation. For each of the sectors modelled, the dashboard shows one page with the results and one for the key levers that can be modified. The dashboard can be used by policymakers and other stakeholders in developing roadmaps for a low-carbon and sustainable Karnataka. For this purpose, as a first step, a sample low-carbon scenario was created in consultation with several experts. This report describes this scenario and its implications. However, it is important to note that the scenario presented is only representative and is intended to demonstrate the tool's capabilities rather than serve as a prescriptive roadmap. As modellers and researchers, we acknowledge that this defines the limits of our study.

The sector-wise key assumptions and expected outcomes of the low-carbon scenario (and the reference scenario for comparison) are briefly described in Table ES1, and the grid electricity demand, power supply capacities, and greenhouse gas (GHG) emissions are provided in Figures ES2, ES3, and ES4, respectively.

Locally developed models, grounded in deep national and sub-national development contexts, should drive the climate action discourse to ensure more equitable and realistic transitions. Models like Namma SAFARI, which enable scenario co-exploration rather than prescribing an optimised solution, foster dialogue on the challenges and trade-offs involved in climate action.

– Dr Tejal Kanitkar, Associate Professor,
National Institute of Advanced Studies (NIAS)

Table ES1: Summary of scenario narratives

Sector	Reference scenario	Low-carbon scenario
Buildings	The built area expands as population and incomes rise, and the construction materials and designs follow current trends. For instance, the share of burnt clay brick in construction remains around 45%–50% up to 2050, and we see a rise in technologies such as Mivan (monolithic structure / aluminium formwork system), which lead to higher energy and emission footprint. On the operational front, a shift towards high-efficiency appliances is assumed even in the reference scenario because Karnataka is one of the leading states in energy efficiency implementation. Rooftop photovoltaic (RTPV) adoption in residential and commercial buildings increases to around 5.4 GW by 2050 (meeting the 1 GW by 2027 target).	Similar to the reference scenario, the built area expands, but there is a shift towards better construction materials (such as autoclaved aerated concrete, hollow clay bricks, stabilised earth blocks, and fly ash bricks) and a complete phase-out of burnt clay bricks by 2050. Mivan-like technologies do not rise as much and are limited to 10% of new construction in the coming decades. Increased adoption of passive cooling options, such as cool roofs and wall insulation, is seen, and RTPV capacity reaches 50 GW by 2050. There is also a shift towards cleaner cooking fuels—to LPG in the short term and electric cooking in the long term.
Steel Industry	Karnataka continues to be a significant steel-producing state, given that it has the third-largest iron ore reserves in the country. In the reference scenario, coal-intensive blast furnaces (BF-BOFs) continue to be used for the majority of steel production, with minimal use of scrap steel and electric arc furnaces (EAFs). The sector continues to produce almost 50% of industrial energy emissions in the state.	No additional BF-BOF plants are built (existing plants are allowed to operate until retirement), and the industry slowly shifts towards EAF-based production powered by green hydrogen once it becomes cost-competitive (post-2040). The scrap steel fraction is assumed to increase to 35% by 2050, the use of auxiliary reducing agents such as hydrogen and biochar also increases to 30% by 2050, and an overall energy efficiency improvement is assumed. These measures also reduce the demand for iron ore. Moving away from coal-powered captive plants towards clean electricity Green Energy Open Access (GEOA) regulations is also considered.

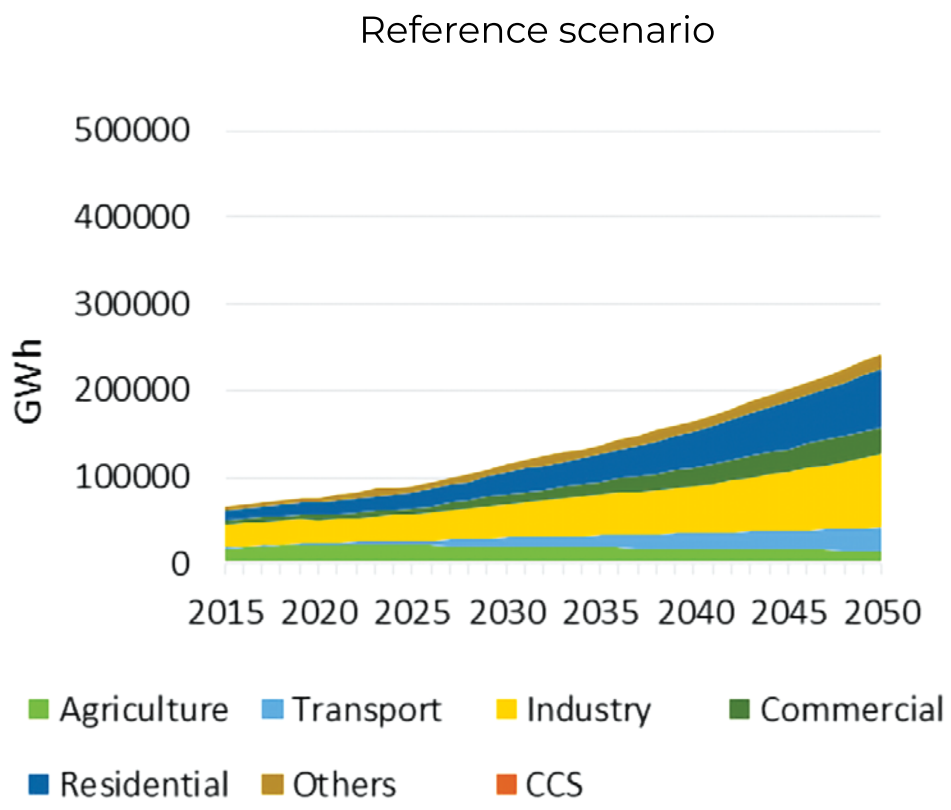
Sector	Reference scenario	Low-carbon scenario
Cement Industry	Cement production in the state continues to be dominated by Ordinary Portland Cement (OPC), followed by Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). Existing efforts towards the increased use of alternative fuels (thermal substitution), such as municipal solid waste, continue but no drastic measures are taken (the fuel share remains at 5%).	Material efficiency measures (pre-cast and onsite blending) lead to a reduction in demand, the share of PSC increases, and the overall clinker-to-cement ratio is brought down to 0.75 by 2030 and 0.5 by 2050. Further, an increased share of alternative fuels (20%; in the short term) and a shift towards electric kilns (in the long term) are envisaged in this scenario. Carbonation in cement kiln dust and GEOA (e.g. for steel) are also considered.
Other Industries	The other key industries in the state, namely, aluminium, fertiliser, refineries, pulp and paper, and textiles, continue existing trends and practices.	Improved energy efficiency and electrification and increased use of grid electricity (or GEOA) are the key levers used in this scenario.
AFOLU	Crop cultivation covers over 60% of the state's geographical area currently and is expected to rise further until all fallow land runs out. Current trends in crops grown, irrigation rates, solar pump uptake, and afforestation continue without any drastic changes.	Crop diversification to grow more millets is assumed, in addition to an increased share of micro-irrigation (75% by 2050), increased organic farming, and increased solar-based irrigation (100% by 2050).
Transport	Current trends in modal shares and fuel shares are assumed to continue, and by 2050, 20%–30% of two-wheeler passenger-kilometres and 5%–10% of buses and car passenger-kilometres are considered to become electric. On the freight side, road transport and diesel consumption continue to play the dominant roles.	A modal share shift towards buses, metro, and railways (particularly for freight) is assumed, along with increased levels of electrification across modes. Rail-based freight transport is accelerated to reach 33% by 2030 and over 40% by 2050.
Power	The power sector continues to expand to meet the state's growing needs. Having high renewable energy (RE) potential, even in the reference scenario, almost 75 GW of RE (solar + wind + firm and dispatchable renewable energy [FDRE]) will be operational by 2050. However, in this scenario, coal does not phase out completely.	In this scenario, the power sector has to cater to a higher electricity demand coming from other sectors owing to increased electrification. Here, we assume that no new coal plants will come on board and existing thermal power plants (TPPs) will retire by mid-century (a little after 2050). This results in a higher uptake of RE (of over 335 GW, compared with 75 GW in the reference).

Understandably, the low-carbon scenario leads to a higher electricity demand (as shown in Figure ES2), dominated by the industry sector due to higher rates of electrification (and green hydrogen use). This shifts the burden of decarbonisation to the power sector, which, under a 'no-new-coal' mandate, adds more renewable energy plants, as shown in Figure ES3. By 2050, the state's GHG emissions can be brought down to around 50 MT compared with over 400 MT in the reference scenario (Figure ES4).

While the scenarios described here are illustrative, they present tangible pathways to achieve a low-carbon future for Karnataka.

Cement and concrete are the second-most consumed materials globally after water, making their decarbonisation critical to achieving climate goals. With most of India's urban infrastructure yet to be built and a national net-zero emissions target set for 2070, decarbonising the cement and concrete industry is both essential and timely. As an inherently carbon-intensive sector, the cement industry in India and globally is actively adopting low-carbon technologies and practices. Models like SAFARI that integrate industry decarbonisation levers and policy options are vital for understanding their overall impact on the broader system.

– Mr Kaustubh Phadke, India Head,
Global Cement and Concrete Association (GCCA)



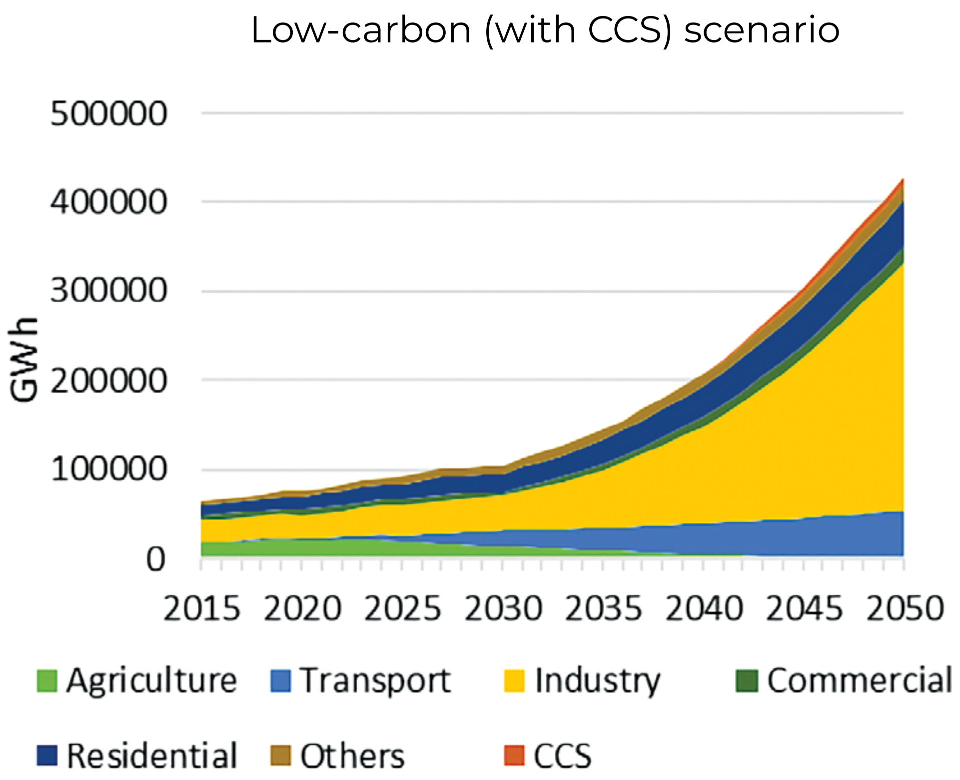
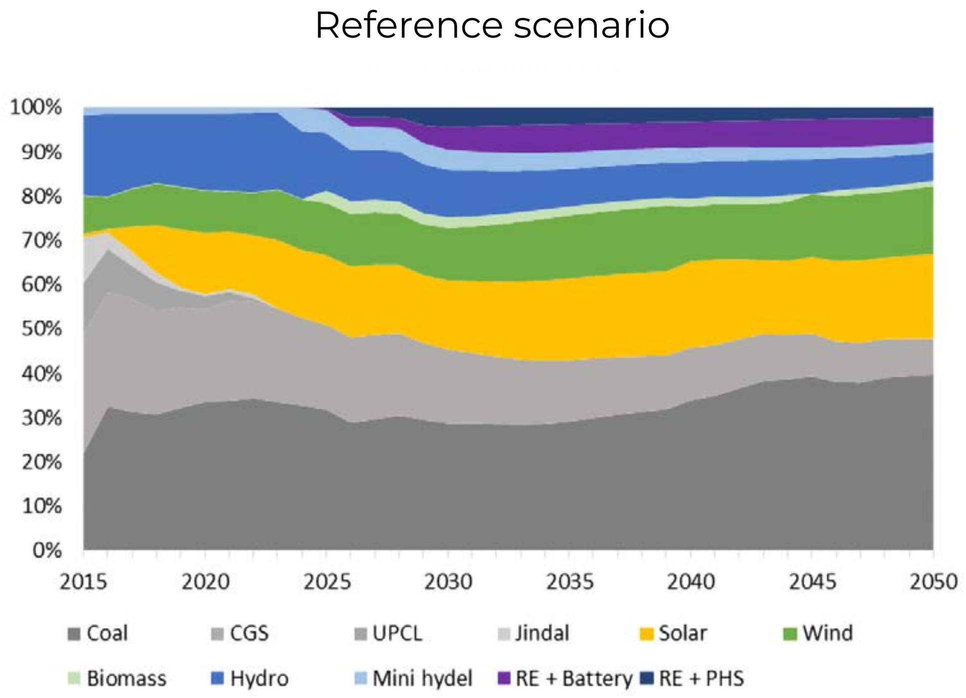


Figure ES2: Grid electricity demand in Karnataka



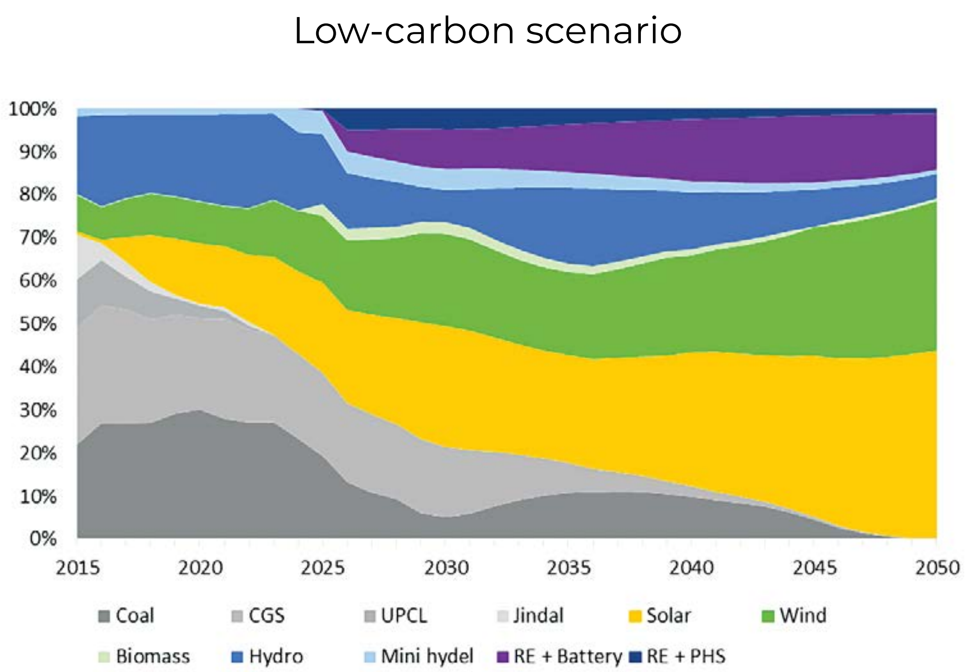
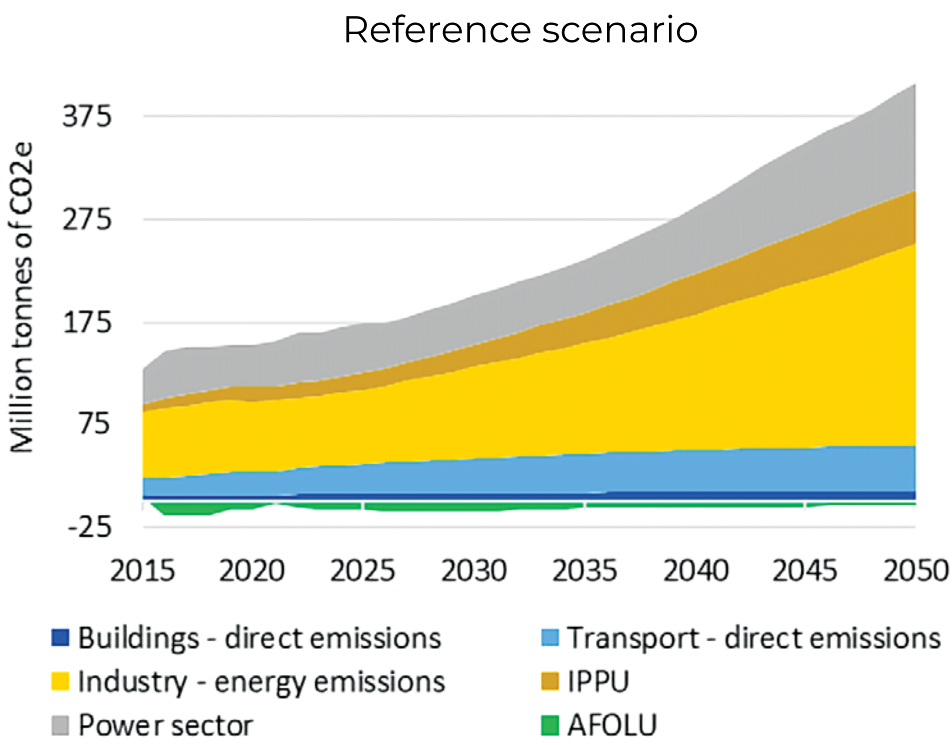


Figure ES3: Power sector generation in Karnataka



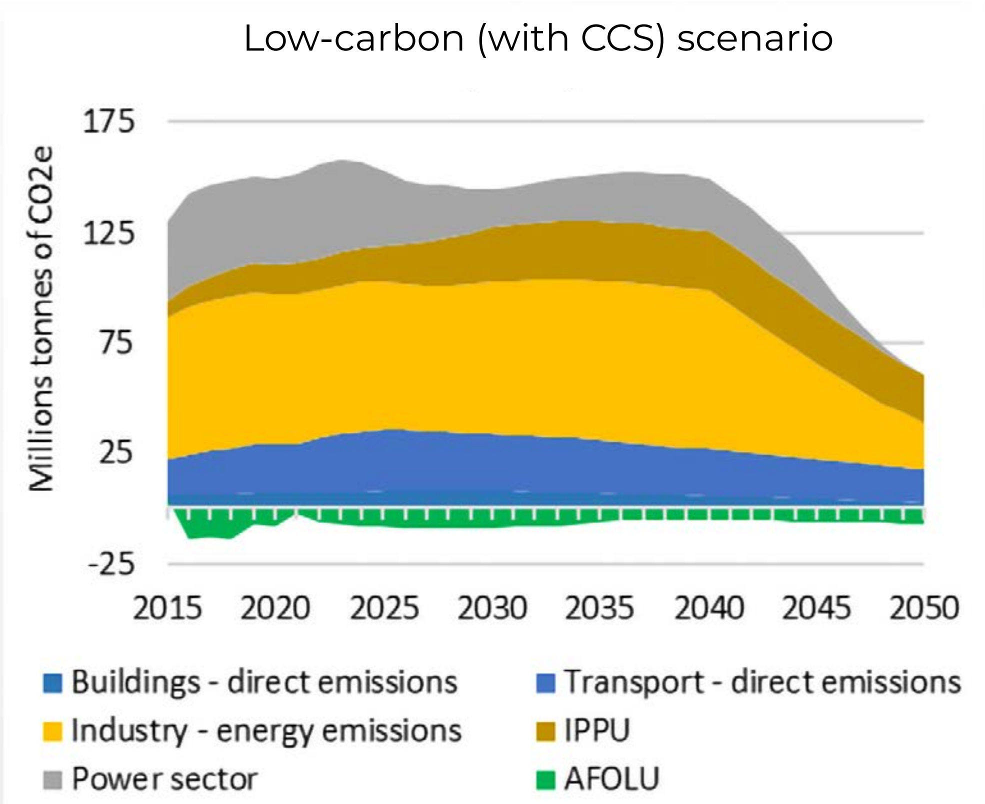


Figure ES4: GHG emissions in Karnataka

Based on our analyses of the scenarios, some focus areas that can be included in a low-carbon roadmap for Karnataka are given below:

Passive cooling strategies and green buildings: In the reference scenario, the buildings sector contributes significantly to electricity demand (~25% of current demand, increasing to almost 40% of the total by 2050). This is primarily driven by space cooling demand. However, in the low-carbon scenario, owing to the increased adoption of passive cooling strategies, green building codes, and RTPV, there is a 25% reduction in electricity demand by 2050 (compared with the reference scenario). Some passive cooling strategies, such as alternative construction / walling materials, limiting the use of Mivan, also reduce embodied emissions from the buildings sector. Thus, overall, these practices are a win–win for thermal comfort, resilience, and emission abatement. Enforcing building codes (such as ECBC and ENS) is, therefore, essential.

Green procurement for cement and steel: Industry is one of the most hard-to-abate sectors but also the largest contributor to electricity demand and emissions. To guarantee demand and drive economies of scale, a mandate for a minimum share (~25%) of public infrastructure projects to use certified green cement or steel, along with preferential pricing for compliance, would boost investment in low-carbon production. Decarbonising these industries also has other co-benefits. For example, increased use of scrap steel in the low-carbon scenario leads to a 35% lower demand for iron ore compared with the reference scenario in 2050.

Unlock the full potential of GEOA regulations: As industries electrify more processes, depending on coal-powered captive plants defeats the whole point. In the low-carbon scenario, emissions from captive power plants will reduce to 0.01 MT by 2050 (compared with 23 MT in the reference scenario). The GEOA regulations could help boost industrial decarbonisation, but strategies to address challenges in enforcement are needed—for instance, waiving surcharges (central rules on cross-subsidy charge waivers); promoting aggregation for micro, small, and medium enterprises (MSMEs); and designing competitive green tariffs where gaps exist to create a win–win situation for both industry and distribution companies (DISCOMs).

Crop diversification in addition to solar pumps and micro-irrigation: The agriculture sector consumes almost 30% of the total electricity in Karnataka and is, therefore, crucial to look at for demand-side management. In addition to solar pump and micro-irrigation adoption, which is progressing well, crop diversification should be incentivised by expanding Minimum Support Price (MSP) procurement coverage for crops such as millets, pulses, and oilseeds (which is currently at 8% vs 45% for rice/wheat).

A freight modal shift policy for the state: Road-based freight is one of the largest contributors to diesel demand and GHG emissions from transport. Currently, only 25% of Karnataka's freight moves by rail (vs 75% by road), despite it being cheaper per tonne-km. In the low-carbon scenario, shifting road to rail freight (33% by 2030) leads to annual diesel savings of almost 50 crore litres. To enable this switch, the state could consider funding last-mile connectivity, particularly to MSME clusters; offer tax rebates for companies using rail; and set a target for rail share for freight in alignment with the Indian Railways.

RE + Storage: With all sectors going electric, the trajectory of the power sector will determine the success or failure of low-carbon development goals. Key enablers include mandating storage for new RE projects or having FDRE plants, unlocking pumped hydro storage and making it profitable through energy arbitrage, and supporting battery storage (e.g. by setting up manufacturing facilities).

While the scenarios described here are illustrative, they present tangible pathways to achieve a low-carbon future for Karnataka. The state's leadership in renewables and industry positions it to pioneer a just transition—balancing equity, affordability, and sustainability. Achieving this vision demands bold policy innovation, stakeholder collaboration, and iterative use of tools such as *Namma* SAFARI to test real-world trade-offs.

Contents

Figures

Tables

Abbreviations

AAC	Autoclaved aerated concrete
AFOLU	Agriculture, forestry, and land use
BEE	Bureau of Energy Efficiency
BF-BOF	Blast furnace-basic oxygen furnace
CCS	Carbon capture and storage
CO_2	Carbon dioxide
COP26	26th Session of the Conference of the Parties
CSCAF	Climate-Smart Cities Assessment Framework
CSEB	Compressed stabilised earth block
EAF	Electric arc furnace
ECBC	Energy Conservation Building Code
ENS-R	Eco Niwas Samhita Karnataka
EV	Electric vehicle
FDRE	Firm and dispatchable renewable energy
GDP	Gross domestic product
GEOA	Green Energy Open Access
GHG	Greenhouse gas
GSDP	Gross State Domestic Product
GW	Gigawatt
KPTCL	Karnataka Power Transmission Corporation Limited
kWh	Kilowatt-hour
LPG	Liquefied petroleum gas
$MtCO_2e$	Million tonnes of carbon dioxide equivalent
MTPA	Million tonnes per annum
OPC	Ordinary Portland Cement
PPC	Portland Pozzolana Cement
PSC	Portland Slag Cement
RE	Renewable energy
RTPV	Rooftop photovoltaic
SAFARI	Sustainable Alternative Futures for India
SAPCC	State Action Plan on Climate Change
SDG	Sustainable Development Goal
TPP	Thermal power plant









1. Introduction

There is no doubt that climate change is upon us and wreaking havoc. Effectively dealing with this crisis requires meticulous planning to develop robust strategies that focus not only on greenhouse gas (GHG) emission mitigation but also on sustainability and resilience. India has set several ambitious targets in this regard, including a net-zero emission goal for 2070 announced during the 26th session of the Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (MoEFCC, 2022). Following this, some states also announced their net-zero targets. Creating strategies to achieve these long-term targets needs comprehensive modelling of all sectors of the economy, considering the key drivers of growth, constraints, and levers of change, including policies and technologies. In this context, the Center for Study of Science, Technology and Policy (CSTEP) developed the Sustainable Alternative Futures for India (SAFARI) model for the country (CSTEP, 2021), which has now been customised for the state of Karnataka (named KA-SAFARI or *Namma* SAFARI). This report outlines the model development process, presents insights at both sectoral and economy-wide levels, and showcases illustrative low-carbon scenarios to demonstrate the model's capabilities.

1.1. Imperative for Karnataka to shift to a low-carbon future

While national targets provide the much-needed direction, a bottom-up approach initiated at the state level can lead to more practical and action-driven pathways. In India's pursuit of net zero, states play a pivotal role in laying the foundation for this transition. Each state is unique in terms of the industry contribution to its economy and the type of industry that the state houses, local energy mix, renewable energy (RE) potential, built environment, land-use patterns, and availability of naturally occurring reserves. Therefore, it is crucial for every state to integrate a tailored climate agenda into its broader economic development aspirations and plans.

Karnataka, with approximately 5% of India's population, was the fourth-largest contributor (8.2%) to the country's gross domestic product (GDP) in FY23 (Deloitte, 2024). In 2023–2024, the state secured the fourth position on India's Sustainable Development Goal (SDG) Index, achieving the highest score in SDG 7 (Affordable and Clean Energy), along with strong performance across several other goals, as shown in Figure 1 (NITI Aayog, 2024). To promote sustainable development and enhance climate resilience, the state also revised its State Action Plan on Climate Change (SAPCC) in 2021, which was approved by the Central Government in 2024. The document sheds light on the GHG implications of the current policies and provides insights on the mitigation strategies to be prioritised by the state for a low-carbon pathway up to 2030 (EMPRI, 2021).

Endowed with a large RE (solar and wind) potential, Karnataka will play a key role in the 'green growth' of the nation. However, the state is yet to formulate a long-term plan towards the transition or announce a net-zero target. A portfolio of active and passive measures across sectors would be essential to achieve the objective. All sectors that are crucial to achieving the SDG goals, such as agriculture, industry, buildings, transport, and energy, also contribute towards GHG emissions and are interlinked. Therefore, it is essential to understand the synergies and trade-offs between attaining SDGs and their associated GHG implications at the state level. A comprehensive strategy to achieve net zero, when implemented, would invariably have the co-benefits of achieving SDGs and other developmental and environmental goals. Therefore, it is crucial for the state to plan for such a transition right away.

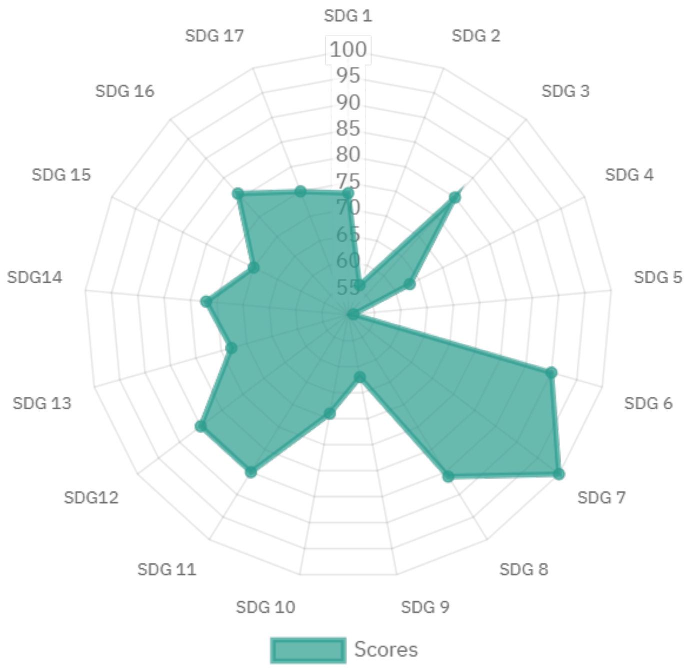


Figure 1: Karnataka's performance across SDGs by NITI Aayog in 2023–24

1.2. Karnataka: Front-runner in RE and energy efficiency

Karnataka is already a leader in some major initiatives, such as greening the electricity generation system and increasing energy efficiency. It is one of the top five states in the country with respect to RE potential, with an estimated 124.15 GW of wind (120-m hub height) (Ministry of New and Renewable Energy, 2025) and 24.7 GW of solar (India Climate and Energy Dashboard, 2025). The state's total RE potential also includes biomass, co-generation, waste-to-energy, and small hydro-based potentials (Energy Department & Government of Karnataka, 2022). Karnataka has been one of the first states to develop RE policies (since 2009), making it a pioneer in the green energy segment. The state is home to the third-largest (6.6 GW) wind capacity and fourth-largest (8.8 GW) solar installations in the country (as of July 2024) (Ministry of New & Renewable Energy, 2024). According to the '2024 Indian States' Electricity Transition' report, Karnataka is one of the states that have demonstrated sufficient readiness to lead the electricity transition, have successfully incorporated RE into their power sectors, and have strong market enablers to support the expansion of clean electricity in the future. However, a large part of the available renewable potential in the state remains untapped. Additionally, the advancement of technologies (e.g. performance improvements and efficiency gains) in solar, wind, and energy storage, combined with the falling cost of technologies and the rise in demand for affordable RE all over India, provides Karnataka with the opportunity to develop more RE projects.

Furthermore, the state has prioritised energy efficiency improvements across sectors through the Karnataka Energy Conservation and Energy Efficiency Policy 2022–2027. It constitutes an overarching framework for the establishment of energy efficiency measures with tailored strategies for each sector. It spotlights enforcement mechanisms and capacity building to realise the scope of energy-saving potential in each sector. For instance, in the buildings sector, it emphasised and adopted the Karnataka Energy Conservation Building Code (ECBC) to promote the construction of energy-efficient building envelopes and the use of energy-efficient appliances, while in the agriculture sector, it mandated the use of the Bureau of Energy Efficiency (BEE) star-rated pumps with improved efficiency for irrigation. Altogether, the policy aims to reduce electricity consumption by around 744 million kWh and thus avoid almost 6,10,080 tonnes of CO_2 emissions by the end of the policy period (Karnataka Renewable Energy Development Ltd, 2022). Thus, being the only state in the country with an active policy focusing on energy conservation and energy efficiency with commendable achievement in the buildings sector, Karnataka emerged as a leading state as per the State Energy Efficiency Index in 2023 (Bureau of Energy Efficiency & Alliance for an Energy Efficient Economy, 2024).

1.3. State policies as a key driver of change

The Karnataka Government continues to play a pivotal role in catalysing change in the state by constituting policy frameworks encapsulating social, economic, and environmental aspects in its developmental initiatives. The progress of the state is backed by several such policies driving its transformation towards a low-carbon economy. These policies aim to operationalise sustainability by integrating it with climate action. The following are some of the pivotal policies developed by the state since 2015:

The Karnataka Renewable Energy Policy 2022–2027 focuses on boosting the RE capacity of the state with a special emphasis on solar, wind, and biomass energy. A target of 10 GW RE generation, including 1 GW of rooftop photovoltaic (RTPV), has been set. It also emphasises the development of necessary infrastructure for RE integration and offers incentives for the transition (Energy Department & Government of Karnataka, 2022).

The Karnataka Electric Vehicle and Energy Storage Policy 2017 aimed to support electric vehicle (EV) manufacturing and deployment of EV batteries, along with the development of the necessary charging infrastructure by attracting investments. Continuing the effort, the updated state EV policy also aims to create a conducive environment for EV adoption by fostering public–private partnerships and encouraging research and innovation (Commerce & Industries Department, 2017).

Similarly, several other policies, such as Karnataka Energy Conservation and Energy Efficiency Policy 2022–2027 (2022), Karnataka Industrial Policy 2020–2025 (2020), and Karnataka Affordable Housing Policy (2016), encourage innovation and technological advancements vital for the shift towards a sustainable green economy.

While such policy initiatives can act as drivers of change in associated sectors, it is crucial to identify their impacts across sectors as they are interlinked and form a complex system. For instance, the Karnataka Renewable Energy Policy, which aims to decarbonise the sectors by promoting electrification through renewable sources, impacts the agriculture sector by solarising feeders and pumps, the transport sector by promoting EVs, and the buildings sector by accelerating the adoption of RTPV. Given the tremendous potential for well-designed policies to transform associated sectors, gaining a holistic understanding of their impact is vital, as such policies may have ripple effects in unanticipated ways. The multifaceted impact relations of some of the current policies adopted in allied sectors in Karnataka are shown in Figure 2.

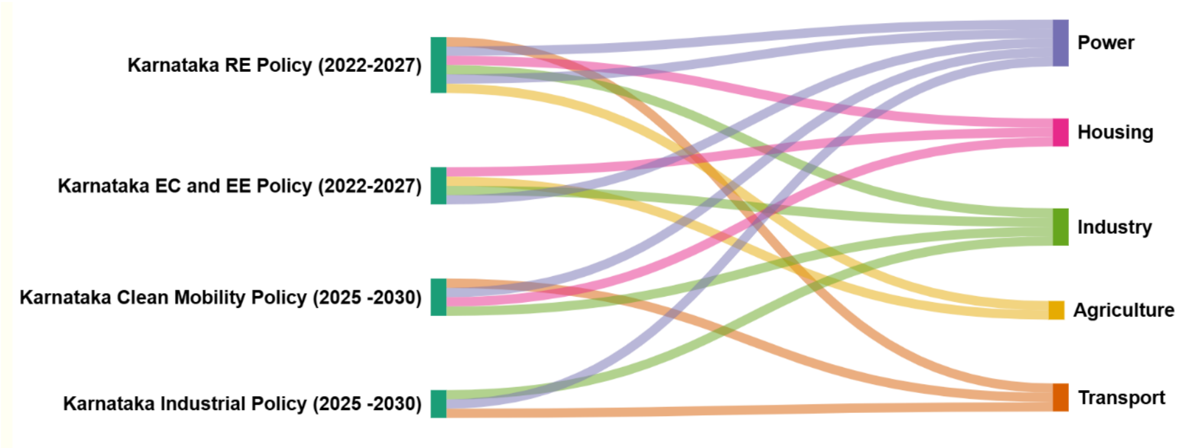


Figure 2: Interlinkages of various policies across sectors in Karnataka

Karnataka is at a unique juncture, as it has gained sufficient momentum to be at the forefront of achieving India's long-term vision of net zero by 2070. Although the state is a forerunner in effective grid integration of renewables and increasing energy efficiency, to promote sustainable growth and green transition, the state must prioritise comprehensive strategy formulation and embrace other initiatives to achieve net zero. Developing a strategic outlook for the state by integrating various sectoral interactions will be beneficial to gain a systemic understanding. Analysis of the interactions among different sectors, such as buildings, transportation, industry, agriculture, and power, can aid informed decision-making for upcoming policies and strategies to develop a future perspective on the sustainable low-carbon pathway for the state.

1.4. Report preview

This report explores some of the complex and often overlooked challenges for Karnataka using *Namma* SAFARI. Karnataka was selected as the first state-level study region for the modelling study to develop a decarbonisation pathway. The process involved data collection and integration, systems modelling, scenario development, policy alignment, and stakeholder engagements at various levels. The state-level model built in this study can be used to design a roadmap for Karnataka up to 2070 with clear sectoral milestones. Depending on the implementation of various interventions, this tool can be used to generate several scenarios as required. *Namma* SAFARI can thus facilitate a better understanding of the state's long-term future. By focusing on the key interventions in each phase of its progression, the state can be well-equipped to embark on the journey of low-carbon development and improved climate resilience. Chapter 2 briefly describes the approach (details in Appendix), followed by sector-wise discussions in Chapter 3 (industry), Chapter 4 (buildings), Chapter 5 (transport), Chapter 6 (agriculture, forestry, and land use [AFOLU]), and Chapter 7 (power). Finally, Chapter 8 presents a few illustrative integrated pathways for the state.

2. Study Approach

2.1. Overall approach

Figure 3 depicts the overall study approach, and each step is described below:

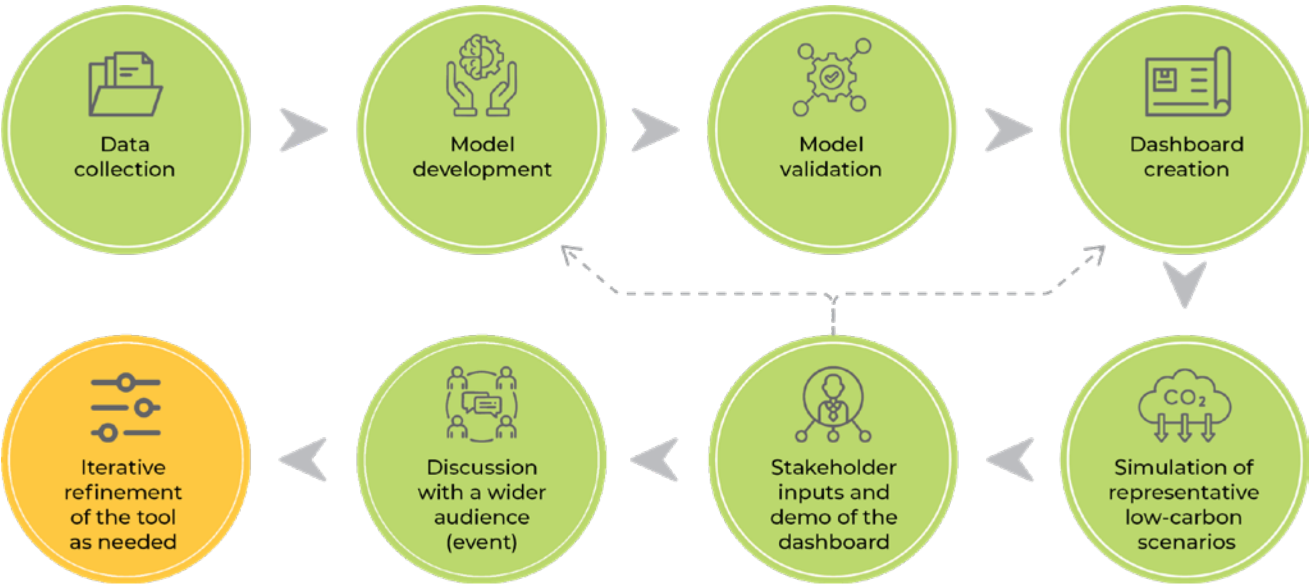


Figure 3: Study approach

- **Data collection:** The first step involved a detailed literature review for collecting data from multiple sources, as listed in the Appendix.
- **Model development:** A causal loop diagram was created for each sector to identify key variables and their interdependencies. This was then developed into a quantitative and robust system dynamics model that projects energy demand and emissions across sectors of interest. The key focus was on capturing the cross-sectoral linkages between sectors.
- **Model validation and calibration:** All standard model tests were performed to ensure model robustness. For all key parameters, model runs for the historical years 2015–2022 (backcasting) were compared with actual data to validate model logic and assumptions, in particular. For instance, the state's electricity demand from different sectors in the model was validated against Karnataka Power Transmission Corporation Limited (KPTCL) data.
- **Dashboard development:** Each sector in the model has a few illustrative mitigation levers to mimic behavioural and policy changes that can influence the total emission values. These mitigation levers can be utilised to create scenarios. An interactive dashboard was created for each sector, allowing users to simulate custom scenarios by experimenting with different combinations of these sector-specific mitigation levers. The dashboard also provides users with insights into the impact of technological and policy options over both the short-term and long-term future.
- **Scenario building and analysis:** Illustrative scenarios were created to understand the emission reduction potential of each mitigation lever in relation to the current trajectory. This helped identify the strategic enablers for the state's transition to a low-carbon pathway.
- **Expert stakeholder consultation:** The key low-carbon scenarios created were presented to an expert committee comprising government officials and industry experts. Their feedback was incorporated to finalise the scenarios.
- **Event:** We organised an event that brought together relevant entities from the ecosystem. The *Namma* SAFARI tool was employed to co-create scenarios through serious gaming.

- **Iterative refinement of the tool:** We plan to continue engagements, particularly with government stakeholders, to ensure its usefulness for policy testing in different departments. Towards this, we are in the process of identifying nodal points in the different line departments that have expressed interest in continued engagement.

2.2. *Namma* SAFARI model structure

The '*Namma* SAFARI' model is based on the national-level model named 'Sustainable Alternatives Futures for India (SAFARI)' developed at CSTEP. *Namma* SAFARI is a system dynamics model built exclusively for the state of Karnataka (Figure 4). This simulation model considers exogenous parameters, such as population, urbanisation rate and GDP, as well as development goals driving the energy demand for the state. It captures the complex interactions among various sectors—industry, buildings, transport, AFOLU, and power supply. The primary objective of the model is to estimate the increasing energy demands and related emissions from the various sectors while pursuing development goals, with climate action levers or interventions to enable a low-carbon pathway. The model is also developed with an intricate understanding of cross-sectoral interactions, such as land constraints limiting RE expansion (including solar and wind) and urban form influencing trip lengths in the transportation sector. Thus, a holistic view of decarbonising the state is achieved through an in-depth cross-sectoral analysis. The detailed methodology for each sectoral development is explained in the Appendix.

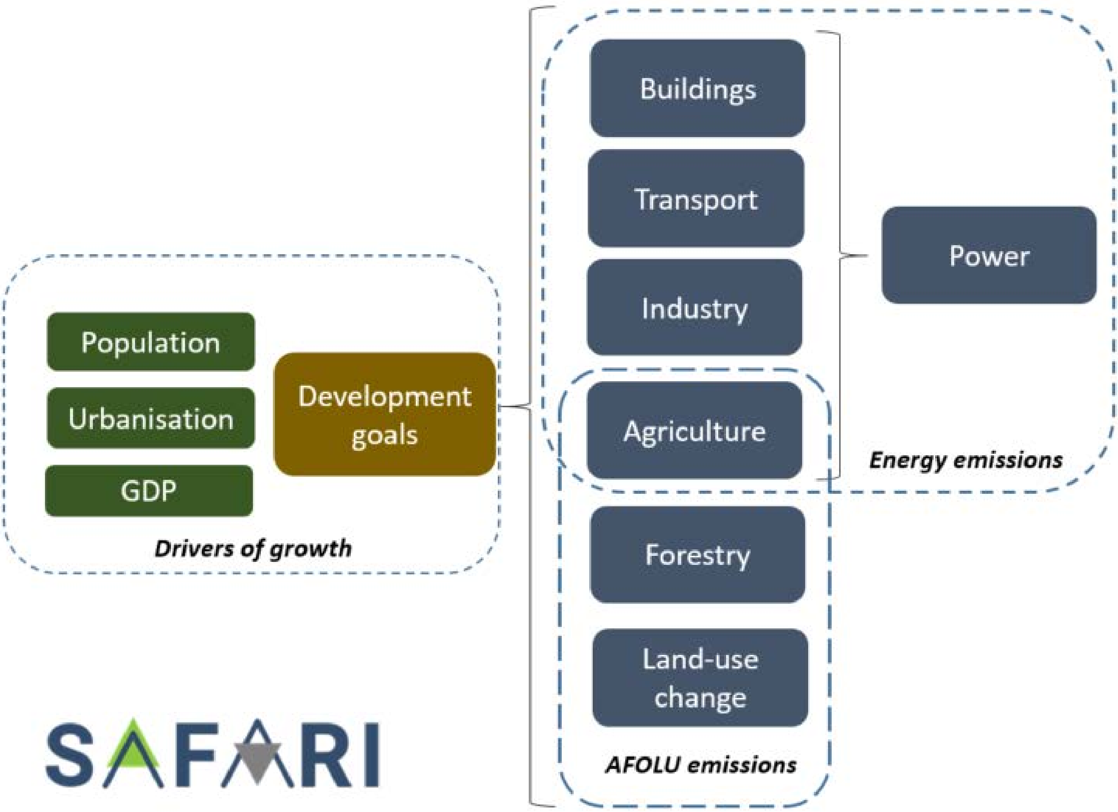


Figure 4: Architecture of Namma SAFARI

2.3. Stakeholder interactions

As part of the efforts to enhance the accuracy and robustness of *Namma* SAFARI, stakeholder engagement was conducted across the project period (Figure 5). The first phase involved individual consultations with various state government departments and key industry experts. During these sessions, a preliminary version of the model was presented to the relevant line departments of the Karnataka Government. This allowed stakeholders to review and provide feedback on aspects such as granularity, assumptions, and baseline projections. Their inputs were carefully evaluated, and recommended changes were incorporated into the model.

The second phase comprised a collective stakeholder engagement event. This event brought together representatives from government departments and private sectors who had previously participated in the individual consultations to facilitate meaningful cross-sectoral discussions among stakeholders.

Figure 5: Stakeholder engagements for the Namma SAFARI model development

The goal of the stakeholder consultations was to collaboratively identify short-term and long-term levers for Karnataka's low-carbon pathway. These insights were subsequently integrated into this report, providing guidance for achieving the state's net-zero targets.

Finally, the report was reviewed by several sectoral experts from industry and the think tank ecosystem.

A detailed list of the participating departments and private stakeholders is provided in the Appendix.

2.4. Projection of GDP and population

Karnataka's GDP was projected based on a shift-share analysis, which decomposes the historical growth observed in Karnataka over the past decade into three components: (a) growth due to the overall growth in India's GDP, (b) growth due to the development of each sector at the national level, and (c) growth due to the competitive advantage possessed by the region with respect to India as a whole (i.e. how much did the economic growth of Karnataka's industry differ from what national and industrial growth trends would predict). Using historical GDP and a conservative estimate of the sectoral growth expected by 2050 at the national level, this decomposition was used to determine Karnataka's state-level and sectoral GDP growth rates.

2.5. Definition of scenarios

Sector	Reference scenario	Low-carbon scenario
Buildings	The built area expands as population and incomes rise, and the construction materials and designs follow current trends. For instance, the share of burnt clay brick in construction remains around 45%–50% up to 2050, and we see a rise in technologies such as Mivan (monolithic structure / aluminium formwork system), which lead to higher energy and emission footprint. On the operational front, a shift towards high-efficiency appliances is assumed even in the reference scenario because Karnataka is one of the leading states in energy efficiency implementation. Rooftop photovoltaic (RTPV) adoption in residential and commercial buildings increases to around 5.4 GW by 2050 (meeting the 1 GW by 2027 target).	Similar to the reference scenario, the built area expands, but there is a shift towards better construction materials (such as autoclaved aerated concrete, hollow clay bricks, stabilised earth blocks, and fly ash bricks) and a complete phase-out of burnt clay bricks by 2050. Mivan-like technologies do not rise as much and are limited to 10% of new construction in the coming decades. Increased adoption of passive cooling options, such as cool roofs and wall insulation, is seen, and RTPV capacity reaches 50 GW by 2050. There is also a shift towards cleaner cooking fuels—to LPG in the short term and electric cooking in the long term.
Steel Industry	Karnataka continues to be a significant steel-producing state, given that it has the third-largest iron ore reserves in the country. In the reference scenario, coal-intensive blast furnaces (BF-BOFs) continue to be used for the majority of steel production, with minimal use of scrap steel and electric arc furnaces (EAFs). The sector continues to produce almost 50% of industrial energy emissions in the state.	No additional BF-BOF plants are built (existing plants are allowed to operate until retirement), and the industry slowly shifts towards EAF-based production powered by green hydrogen once it becomes cost-competitive (post-2040). The scrap steel fraction is assumed to increase to 35% by 2050, the use of auxiliary reducing agents such as hydrogen and biochar also increases to 30% by 2050, and an overall energy efficiency improvement is assumed. These measures also reduce the demand for iron ore. Moving away from coal-powered captive plants towards clean electricity Green Energy Open Access (GEOA) regulations is also considered.

Sector	Reference scenario	Low-carbon scenario
Cement Industry	Cement production in the state continues to be dominated by Ordinary Portland Cement (OPC), followed by Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). Existing efforts towards the increased use of alternative fuels (thermal substitution), such as municipal solid waste, continue but no drastic measures are taken (the fuel share remains at 5%).	Material efficiency measures (pre-cast and onsite blending) lead to a reduction in demand, the share of PSC increases, and the overall clinker-to-cement ratio is brought down to 0.75 by 2030 and 0.5 by 2050. Further, an increased share of alternative fuels (20%; in the short term) and a shift towards electric kilns (in the long term) are envisaged in this scenario. Carbonation in cement kiln dust and GEOA (e.g. for steel) are also considered.
Other Industries	The other key industries in the state, namely, aluminium, fertiliser, refineries, pulp and paper, and textiles, continue existing trends and practices.	Improved energy efficiency and electrification and increased use of grid electricity (or GEOA) are the key levers used in this scenario.
AFOLU	Crop cultivation covers over 60% of the state's geographical area currently and is expected to rise further until all fallow land runs out. Current trends in crops grown, irrigation rates, solar pump uptake, and afforestation continue without any drastic changes.	Crop diversification to grow more millets is assumed, in addition to an increased share of micro-irrigation (75% by 2050), increased organic farming, and increased solar-based irrigation (100% by 2050).
Transport	Current trends in modal shares and fuel shares are assumed to continue, and by 2050, 20%–30% of two-wheeler passenger-kilometres and 5%–10% of buses and car passenger-kilometres are considered to become electric. On the freight side, road transport and diesel consumption continue to play the dominant roles.	A modal share shift towards buses, metro, and railways (particularly for freight) is assumed, along with increased levels of electrification across modes. Rail-based freight transport is accelerated to reach 33% by 2030 and over 40% by 2050.
Power	The power sector continues to expand to meet the state's growing needs. Having high renewable energy (RE) potential, even in the reference scenario, almost 75 GW of RE (solar + wind + firm and dispatchable renewable energy [FDRE]) will be operational by 2050. However, in this scenario, coal does not phase out completely.	In this scenario, the power sector has to cater to a higher electricity demand coming from other sectors owing to increased electrification. Here, we assume that no new coal plants will come on board and existing thermal power plants (TPPs) will retire by mid-century (a little after 2050). This results in a higher uptake of RE (of over 335 GW, compared with 75 GW in the reference).

3. Industry Sector

3.1. Steel industry

Karnataka has the third-largest iron ore reserves, constituting about 16% of India's reserves, and currently contributes to ~14% of the national steel production. Projections based on regression analysis with the state GDP show that the state's steel production can reach 21 million tonnes per annum (MTPA) by 2030, in alignment with the national target of 300 MTPA production capacity by 2030. The iron and steel industry is one of the major manufacturing industries of the state and constitutes nearly 30% each of the state's electricity demand and total emissions. With the business-as-usual (Reference) trend of increasing the share of integrated steel plants using coal-intensive blast furnaces, the share of emissions from the steel sector can increase up to 45% of the projected total emissions from the state by 2070. Greening the iron and steel industry is, therefore, integral to the state's net-zero pathway. The total steel production in Karnataka through different processes is shown in Figure 6.

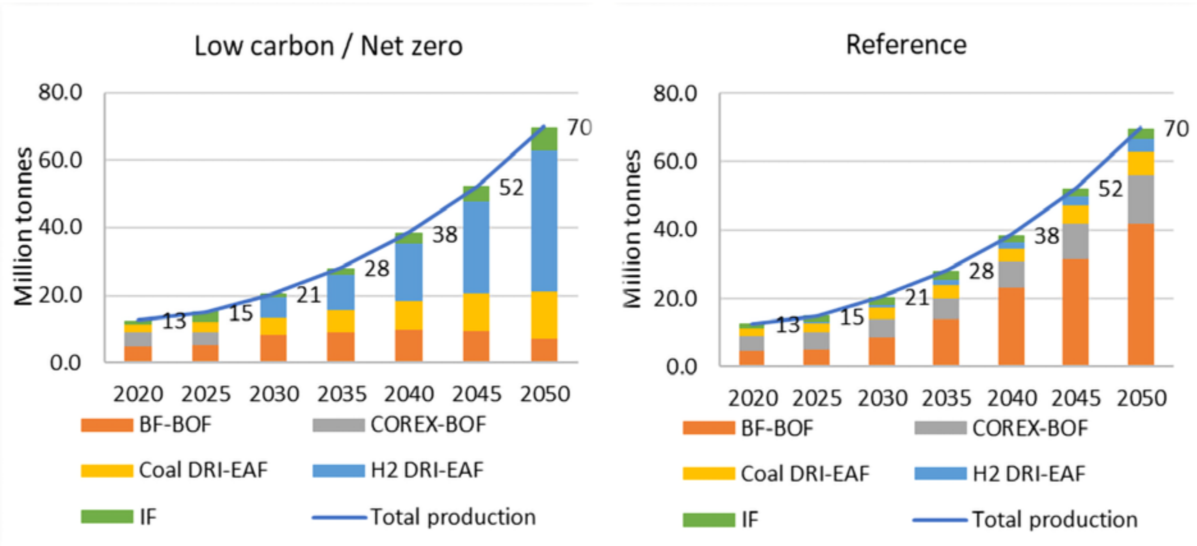


Figure 6: Steel production by various pathways under reference and low-carbon scenarios

3.1.1. Low-carbon trajectory

To achieve emission reductions (both Scope 1 and Scope 2), the steel industry will have to shift to electric arc furnace (EAF)-based production. After analysing the timeline of the current and announced blast furnace-basic oxygen furnace (BF-BOF) plans, this is possible without significant stranded assets if no additional BF-BOF plants are built. From 2040 onwards, assuming that the cost-effective production of electrolytic hydrogen is possible, in the net-zero scenario, the production process shifts increasingly to hydrogen-powered EAFs to meet 60% of the production by 2070. This would entail steel industries requiring hydrogen electrolysers—sufficient to manufacture 1.25 million tonnes of steel (8 GW electrolyser capacity) by 2050. This lever, along with green electricity (from the grid or generated in captive plants), has the highest potential to reduce emissions. The impact of all levers on annual emissions in the short and long term is provided in Figure 7. The other key levers and their assumptions for achieving net zero in this industry are as follows:

- **Scrap fraction:** The availability of scrap is expected to increase over time, given the pace of development, scrapping, and resource-efficiency policies. The scrap fraction in BOF increases to 35% by 2050 compared with 10% in the current trajectory. The scrap fraction in EAF increases to 35% by 2050 compared with 6% under reference case. This saves the energy requirement for ore preparation and iron-making and the use of coke/metallurgical coal. Subsequently, this also results in emission reductions.

- **Efficiency improvement:** The industry average efficiency for all production processes was assumed to achieve the current best available technology levels by 2030.
- **Auxiliary reduction agents:** The coking process in the BF-BOF steelmaking is a major driver of process emissions (Industrial Processes and Product Use). The increased use of greener alternatives such as hydrogen and biochar as auxiliary reduction agents (15% by 2030 and 30% by 2050 compared with 5% in the current trajectory) was assumed. While the impact on net emissions is not significant, it is effective in reducing hard-to-abate process emissions from the coking process in BF-BOF plants.
- **Green electricity:** Given that steel production is highly electricity-intensive, in the net-zero trajectory, an increased share of grid electricity was assumed along with grid decarbonisation.
- **Carbon capture and storage (CCS):** As the last-mile lever to achieve net zero, CCS was assumed to be integrated into the remaining BF-BOF plants from 2040 onwards.

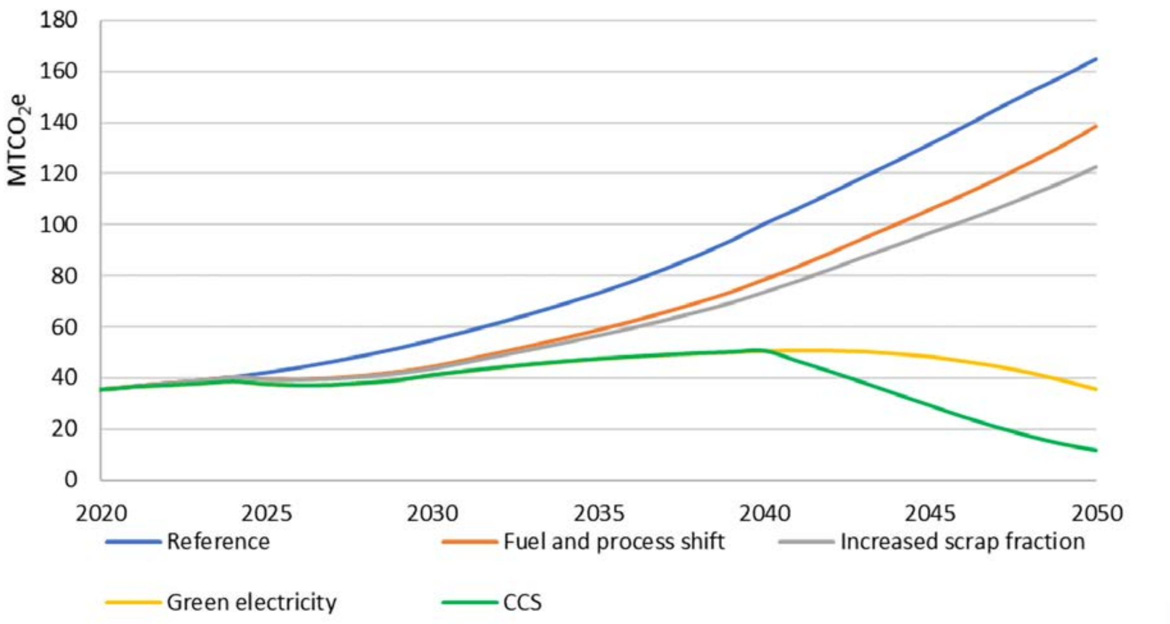


Figure 7: Annual net emissions (Scope 1 and Scope 2) from the steel industry with the interventions

3.2. Cement industry

Cement is one of the largest industries in Karnataka and contributed around 7% of India's total cement production in 2021. Karnataka achieved a total cement production of about 24.9 MTPA in 2021 and 22.6 MTPA in 2022. Currently, this industry contributes almost 25% of the total emissions from Karnataka's industry sector. Based on the regression analysis with the state GDP, the cement sector is projected to grow at an annual rate of about 5% until 2030, beyond which the growth is slowed down to about 2% by 2050. Cement companies in the state are actively working to decarbonise the sector through various measures, such as increasing the production of green cement, increasing the use of RE (solar and wind), and using municipal solid waste (MSW) and alternative fuels to power captive plants. However, because cement is a hard-to-abate sector, further decarbonisation interventions are required. The total production of the three main types of cement in Karnataka, namely, Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and Portland Slag Cement (PSC), is shown in Figure 8.

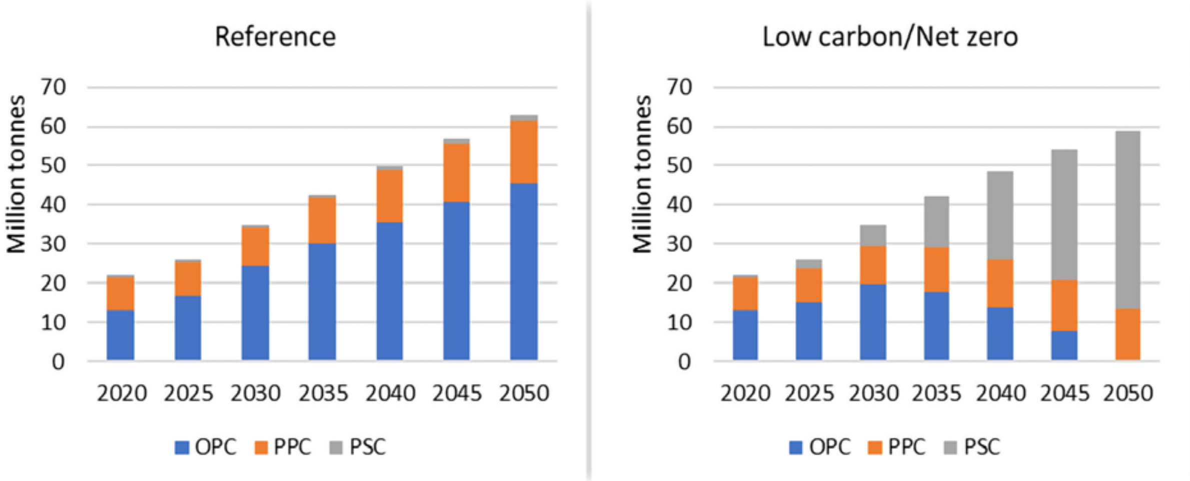


Figure 8: Annual production of cement by type

3.2.1. Low-carbon trajectory

The various levers that can be implemented in the cement industry to reduce energy consumption and emissions are listed below, and their respective effects on the total emissions from the cement sector are shown in Figure 9.

- **Material efficiency:** The demand for cement could be streamlined because of the increasing prevalence of precast concrete and/or onsite blending. We assumed a slow diffusion of these efficient construction practices, leading to a demand reduction of 25% by 2050.
- **Clinker substitution:** The clinker-to-cement ratio is progressively lowered from the reference level of 0.85 to 0.75 by 2030 and further to 0.50 by 2050. This reflects an increased use of supplementary cementitious materials such as fly ash, slag, and calcined clays, significantly reducing the carbon intensity of cement while maintaining performance standards.
- **Fuel shift:** The low-carbon scenario assumed a progressive shift away from the use of coal-based thermal energy for cement production. While the reference trajectory assumes continued low uptake of alternative fuels at around 5%, the low-carbon scenario incorporates a near-term increase in the use of lower-emission alternatives—such as MSW, biomass, and other waste—reaching 20% of the fuel mix by 2030. In the long term, the scenario assumes a more radical shift, with the deployment of electric kilns meeting 50% of the fuel share by 2050, entirely phasing out coal. This transition significantly raises the electricity demand from the sector, which must be procured from a clean source. Given that the cement industry currently relies on captive coal-fired power, achieving emission reductions will require switching to renewable-based captive generation or a predominantly renewable-powered grid.
- **Carbonation in cement kiln dust (CKD):** The scenario assumes enhanced carbonation of CKD as a complementary emission reduction strategy. Recent research (Adekunle, 2024) a byproduct of cement production, holds significant potential as a carbon sink. This review comprehensively examines the physical, chemical, and mineralogical characteristics of CKD, highlighting its suitability for carbon dioxide (CO_2 shows that CKD, which is typically considered a waste byproduct, can sequester a portion of process-related CO_2 emissions through natural and accelerated carbonation. The scenario assumes an increased carbonation rate of CKD, contributing to net emission reduction by capturing CO_2 released during clinker production. This lever enhances the overall carbon sequestration potential of the cement industry and supports the circular use of waste materials within the production process.
- **CCUS:** As the last-mile lever to achieve net zero, CCUS was assumed to be integrated into cement manufacturing plants from 2040 onwards.

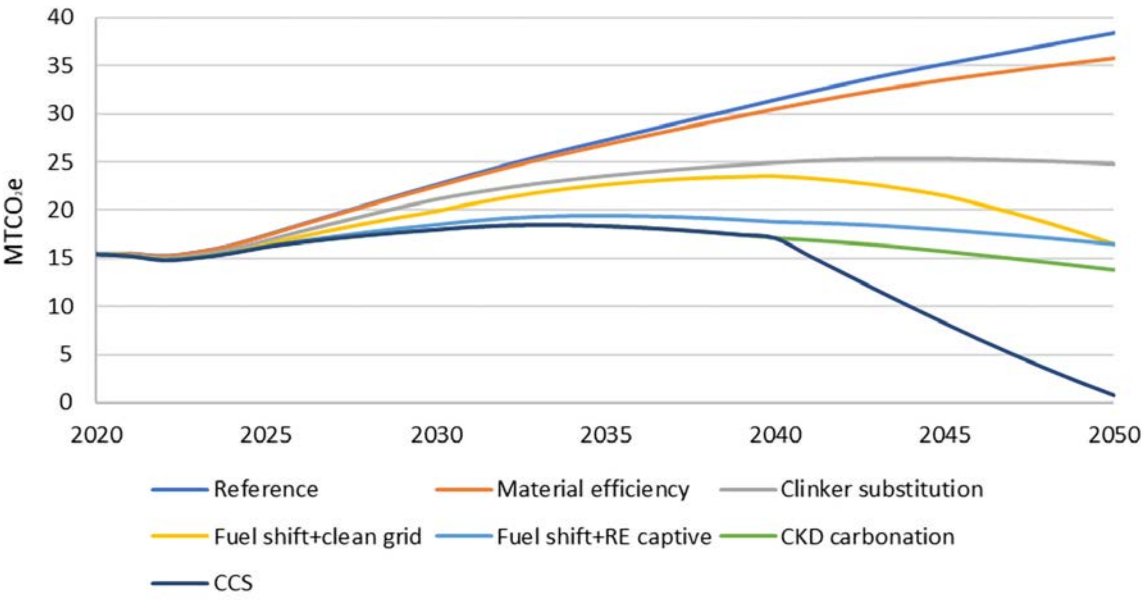


Figure 9: Annual net emissions from the cement sector

The global average for Alternative Fuels and Raw Materials (AFR) replacement is around 19%, and the European Union has achieved a remarkable thermal substitution rate (TSR) of approximately 40% (26% from waste and 14% from biomass). However, India's cement industry is lagging far behind, with an average TSR of just 3%, of which the share of refuse-derived fuel (RDF) is less than 1%.

Karnataka's waste management landscape

In 2021, the state generated approximately 3,476 tonnes per day (TPD) of dry waste. Out of this, only 515 TPD of waste was recycled, 215 TPD was converted into RDF, and 117.88 TPD was co-processed in cement kilns. This left a substantial balance of about 2,638 TPD of dry waste, which ended up in landfills, wasting its potential as a resource.

The dry waste in Karnataka, primarily generated from domestic and commercial activities, contains both biodegradable and non-biodegradable combustible materials. RDF, with a calorific value exceeding 2,000 kcal/kg, can serve as a viable alternative fuel in cement plants or waste-to-energy facilities. However, Karnataka currently lacks operational waste-to-energy facilities, and the state strategy prioritises co-processing in cement kilns over energy recovery from waste. To address the gap, the state has identified the need for 818 dry waste collection centres or material recovery facilities, of which only 217 are operational as of 2021. Additionally, efforts are underway to establish waste-to-energy plants, such as a 600 TPD facility of 11.5 MW that is being built in Bengaluru and a 200 TPD plant in Dharwad.

Challenges in thermal substitution

Despite the evident potential, several barriers hinder the widespread adoption of RDF and other alternative fuels in India. Challenges in municipal solid waste (MSW) processing include uncertainty in demand, risk of rejection, and price volatility. For cement producers, the key concern revolves around the heterogeneous quality of RDF. Despite the introduction of Solid Waste Management (SWM) Rules, 2016, the on-ground implementation remains inadequate. These rules mandate that non-recyclable waste with a calorific value of 1,500 kcal/kg or more should not be disposed off into landfills but instead be used for energy generation or as RDF. Cement plants within 400 km of an RDF facility are required to replace in a phased manner a certain percentage of their fossil fuel intake with RDF, starting with 6% in the first year and scaling up to 15% within 3 years. However, high transportation costs and inconsistent supply chains pose significant obstacles. The Ministry of Environment, Forest and Climate Change released a new draft of the SWM Rules in December 2024. Although the mandate regarding the calorific requirement of waste to be converted into RDF remains the same, the time limit for cement plants to source 15% of their fuel shares from RDF has been revised to 6 years from the date that SWM 2024 is set to come into effect, which is October 2025.

Industry initiatives

Some industry players are taking proactive steps to address these challenges. UltraTech Cement, for instance, has established partnerships with 80 municipal corporations across India and processes 1,24,070 tonnes of MSW annually, including at their Rajashree Cement Works plant in Karnataka. In addition, they utilise 3,39,675 tonnes of non-recyclable plastic waste as an alternative fuel in their plants, aligning their efforts with the Swachh Bharat Mission.

Road ahead

India's cement industry has set ambitious targets to achieve a TSR of 25% by 2025, a significant leap from the current 3%. Achieving this goal is crucial for meeting India's Nationally Determined Contributions (NDCs) under the Paris Agreement. To unlock the potential of RDF and other alternative fuels, coordinated efforts are needed to

- strengthen the infrastructure for waste segregation, collection, and processing;
- ensure consistent quality and pricing mechanisms for RDF; and
- address transportation challenges through innovative funding solutions, such as utilising corporate social responsibility funds.

By overcoming these barriers and fostering collaboration between municipal bodies and the cement industry, India can significantly enhance its TSR, reduce dependency on fossil fuels, and contribute to a sustainable waste management ecosystem. Karnataka, with its ongoing initiatives and strategic vision, has the potential to lead by example, turning waste into a valuable energy resource and promoting a circular economy.

3.3. Other industries

This includes all five core industries in Karnataka other than cement and steel, namely, aluminium, fertiliser, refineries, pulp and paper, and textiles. These industries contribute to less than 10% of the industry sector's total electricity demand and emissions. They are expected to grow annually at a rate of around 3%–6%. Many of these industries comprise only one plant, such as aluminium (Hindustan Aluminium Corporation Limited or HINDALCO), oil refineries (Mangalore Refinery and Petrochemicals Limited [MRPL]), and fertilisers (MRPL). In such cases, implementing decarbonisation measures and monitoring progress is relatively straightforward. However, other industries such as paper and textiles are mainly comprised of micro, small, and medium enterprises (MSMEs) and are therefore highly informal. This leads to difficulties in obtaining data, implementing energy efficiency and decarbonisation measures, providing access to finance, and monitoring and evaluation. Therefore, urgent interventions are required to make these sectors more efficient and reduce their emissions. The total production of other industries is shown in Figure 10.

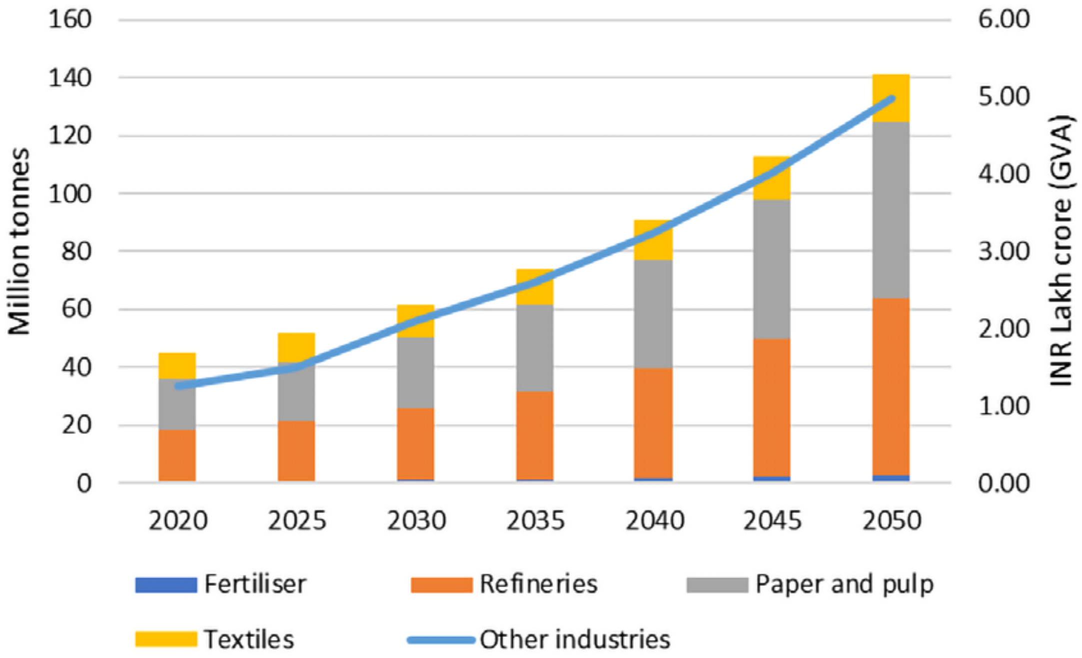


Figure 10: Annual production of other industries

3.3.1. Low-carbon trajectory

Industries in Karnataka, apart from cement and steel, will also play a crucial role in the state's path towards net-zero emissions, given that their total annual productions are projected to increase significantly. Although the current levels of electricity consumption and emissions from industries such as aluminium, fertiliser, refineries, textiles, and paper are considerably less than the cement or steel industry, the informal nature of some of these industries poses significant challenges. Each of the industries such as aluminium, fertiliser, and refineries only have one major plant located in Karnataka, whereas industries such as textiles and paper mainly comprise MSMEs that are spread throughout the state. This necessitates a holistic approach to develop a comprehensive low-carbon pathway to understand the key levers and points where decarbonisation interventions would be most effective. Three main levers were considered for the decarbonisation of these industries:

- **Improved energy efficiency:** There is a significant improvement in energy efficiency across these industries compared with the reference scenario, marked by a reduction in the specific energy consumption (SEC). This could be because of improvements in technology and equipment, access to cleaner fuel, and waste heat recovery. There is a 10% reduction in SEC by 2030 and a 20% reduction by 2050 compared with the reference scenario.
- **Electrification:** These industries gradually switch from high-emitting fossil fuels such as coal and petcoke to electricity and natural gas as a decarbonisation measure. There is a 10% reduction

in the fuel shares of coal and petcoke by 2030 and a 20% reduction by 2050. The fuel shares of electricity and natural gas increase correspondingly.

- **Increased share of grid electricity:** The industries begin to draw more electricity from the grid instead of producing it via captive plants. By 2040, 20% more electricity will be obtained by these industries through the grid. By 2070, 100% of their electricity demand will be met by the grid. The grid also has correspondingly higher fractions of renewable energy. Alternatively, because MSMEs generally work in clusters, increased electricity usage can also come from renewables such as solar parks built within each cluster. For this particular scenario construction, we considered electricity demand to be met by the grid.

The annual emissions from other industries are shown in Figure 11. The reference scenario already shows a reduction in SEC and fuel shares of coal by 2030 and 2050. Notably, the low-carbon scenario assumes an additional decrease of 10% and 20% by 2030 and 2050, respectively, compared with the reference scenario.

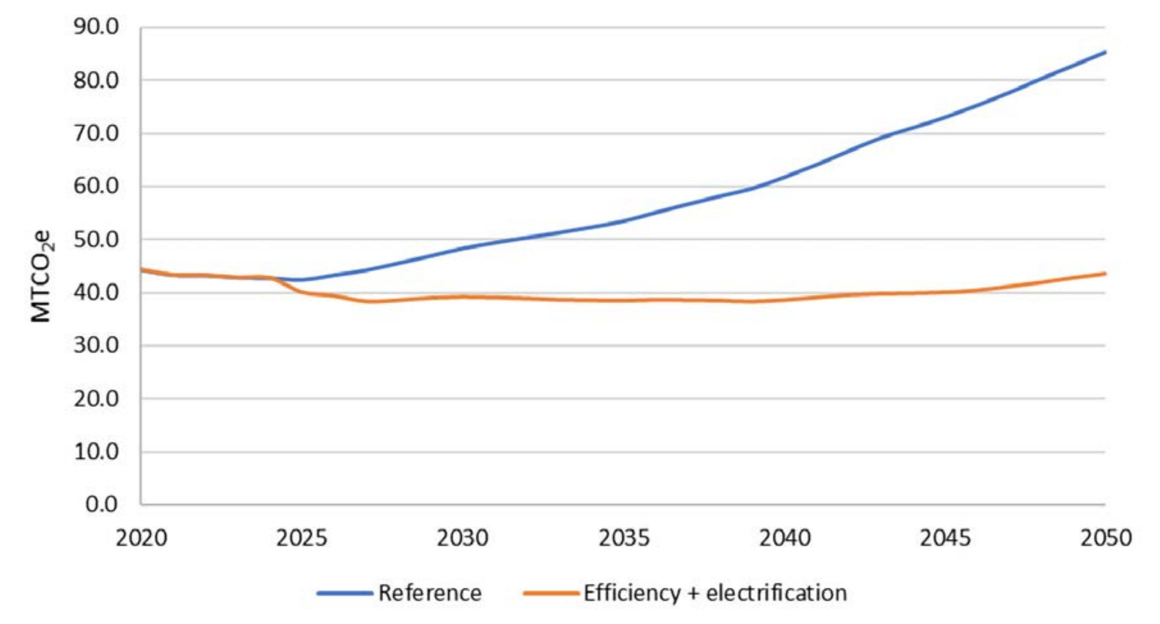


Figure 11: Annual emissions (Scope 1 and Scope 2) from other industries

Of note, there is a slight increase in emissions when the fuel share of electricity is increased without increasing the share of grid electricity. This is because the increased electricity demand will be met by captive power plants, which are still mainly powered by coal, leading to greater emissions. If the share of electricity is increased along with a corresponding increase in the share of electricity demand from the grid with RE having a greater share, there will be a reduction in the total emissions.

3.4. Co-benefits / Cross-sectoral impacts

Electricity demand and power sector transformation: The low-carbon trajectory will lead to a substantial increase in electricity demand, which could be almost three times higher than that under reference in 2050 and six times higher than that under reference in 2070. This shift will significantly shape the power sector, driving the transition towards clean energy sources, grid modernisation, and energy storage solutions.

Alternative fuels and waste management: Increased use of MSW and agricultural residues as alternative fuels in the cement industry and as biochar for ore reduction in the steel industry will address the mounting urban waste problem, reduce crop burning, and mitigate related emissions. This will create value chains for waste streams and improve waste management practices.

Material efficiency and circular economy: Increased emphasis on material efficiency and scrap-based steel production will enable circular economy practices, reducing pressure on mining and forest land. These measures will help conserve resources and protect ecosystems and support sustainable industry growth.

3.5. Key state policy focus for supporting low-carbon industry (2025–2035)

Based on interactions with key industry representatives and model findings, we recommend the following policy focus areas for the state to enable a low-carbon transition for the industry sector:

Karnataka Green Hydrogen Policy: A state-specific green hydrogen policy has not yet been announced but appears imminent, as per media reports. A recent study estimates that Karnataka will contribute only 1% (50 ktpa) of India's 5 million tonnes green hydrogen target by 2030, based on its current share of grey hydrogen production. The total hydrogen demand from the refinery and fertiliser sectors in the state is currently 0.2 MTPA and could rise to 0.28–0.3 MTPA by 2030. As per current trends, only 16% of this demand is expected to be green. Further, hydrogen-based steelmaking, crucial for decarbonising Karnataka's major steel industry, requires substantial investment in hydrogen infrastructure. Leveraging the central budget under the Green Hydrogen Mission and developing a state policy that includes demand assessment and specific targets for steel, along with fertiliser and refinery sectors, are essential. Additionally, a competitive RE pricing policy should be included to ensure cost-effective hydrogen adoption.

Green and reliable electricity: Stakeholders across industries highlighted the critical need for policy reforms to deliver green and reliable electricity. Currently, captive power generation based on coal serves as a major electricity source for large industries but is also a significant contributor to emissions. With the guarantee of clean and cost-effective electricity, the industry sector can be incentivised to shift to grid electricity. Further, as outlined in the previous section, the electrification of industrial processes in the low-carbon trajectory has the potential to increase the electricity demand by multiple folds. To capitalise on this shift, distribution companies should undertake measures that create new revenue streams, such as grid balancing services, and introduce competitive green tariffs to drive the transition effectively.

4. Buildings Sector

With increasing urbanisation in Karnataka, driven by economic growth and infrastructure development, the state is expected to witness a rise in housing demand. This urban transformation will have a long-term impact on the standard of living. Among the additional households that would have migrated to urban areas by 2022, more than half would require affordable housing (KAHP 2016). As rural and urban housing schemes are instrumental in tackling the housing shortage in the state, the reconstruction of kutcha houses is being prioritised as per the Karnataka Economic Survey 2023–2024 (Planning, Programme Monitoring and Statistics Department, 2024). To accommodate this growing housing demand, the total residential built-up area is projected to increase by almost two times by 2050 compared with that in 2020 (Figure 12).

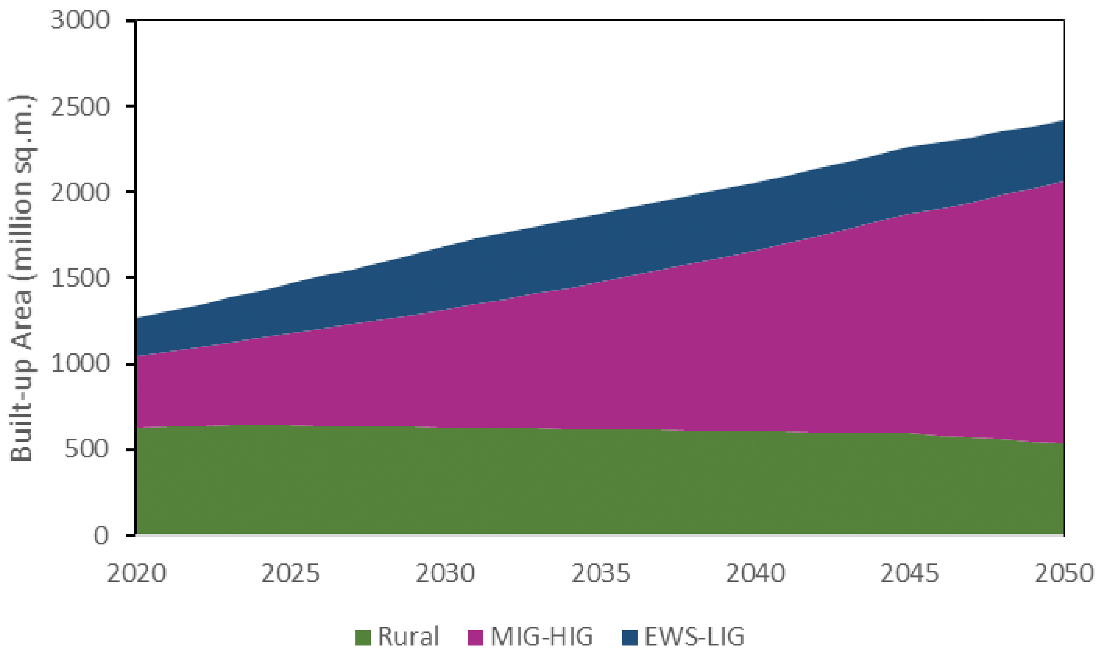


Figure 12: Projected residential built-up area in Karnataka under the reference scenario

As the built-up area continues to expand, the buildings sector is expected to be a major driver for the electricity demand and the power sector. This sector contributed to ~28% of the state's total electricity demand in 2024, and this demand is expected to increase to nearly 42% in 2050 under the reference scenario. A major reason behind this rise in residential electricity demand is the increased adoption of air conditioners owing to the increase in household income and the need for enhanced thermal comfort. Further, as the state aspires to achieve the goal of 'Housing for All', emissions from the residential sector are also expected to rise. Currently, direct emissions from residential buildings account for ~5% of the total emissions, but with indirect and embodied emissions, the total emissions from this sector rise to ~16%. Therefore, it is crucial to devise strategies to mitigate the growing energy demand and emissions from Karnataka's residential sector.

Karnataka aspires to become a USD 1 trillion economy by 2032, and the state's growth is primarily driven by the services sector, contributing to almost 67% of the overall Gross State Domestic Product (GSDP) in 2022–2023 (Planning, Programme Monitoring and Statistics Department, 2023). This growth will be driven by robust investments and a strong pipeline of infrastructure projects across various categories of commercial buildings. Figure 13 shows that the total built-up area for commercial buildings is projected to grow at an annual average rate of 6% based on GDP regression to support rapid urbanisation in the state. The commercial sector currently accounts for 8% of the total electricity demand and can account for up to 15% in the long term.

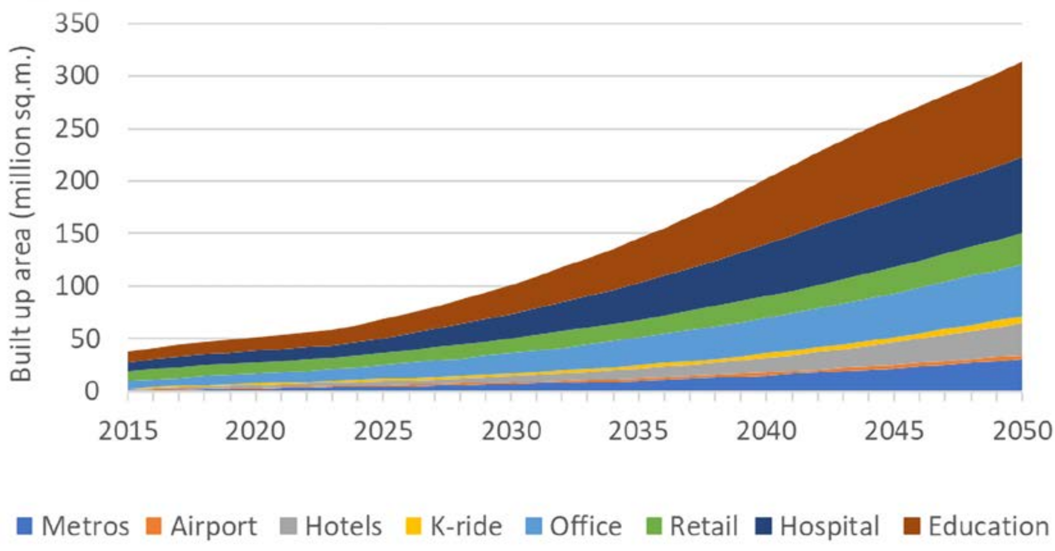


Figure 13: Projected commercial built-up area in Karnataka under the reference scenario

The residential and commercial buildings sectors in Karnataka exemplify the dual challenges of supporting economic growth while ensuring environmental sustainability. The path forward involves balancing developmental aspirations with innovative and sustainable energy strategies to shape the future of Karnataka's built environment and allied sectors.

4.1. Low-carbon trajectory

Given the rising energy demands from the residential buildings sector under the reference scenario, a low-carbon trajectory was developed to meet the growing need, reduce the estimated emissions, and promote a sustainable development strategy for the sector. This alternate pathway includes a set of interventions that can create a profound impact on the emission profile. Although increased construction for housing and commercial needs can lead to a marginal rise in the total emissions in the short term, adopting various passive building design techniques in newly constructed buildings can help minimise the overall emissions from the sector in the long term.

The following interventions are recommended for the development of a low-carbon trajectory for the buildings sector:

- Passive cooling strategies in residential buildings
  - **Increased adoption of cool roofs:** The conventional roof area is converted to cool roofs, and the share of green roofs increases over other cool roof categories such as coated, membrane, and tiled cool roofs, gradually reaching 100% of the total available roof area in residential buildings by 2050. This intervention helps reduce the sensible heat gain through roofs and thereby reduces the cooling energy demand.
  - **Optimising window characteristics:** The percentage share of new residential buildings adopting an efficient window-to-wall ratio increases over the years and reaches 100% by 2050, as it helps control heat gain in the building while maximising natural lighting. Windows with double glazing, low-emissivity glass, and lower solar heat gain coefficient are constructed in the new buildings, considering a major portion of Karnataka falls under the warm and humid climate zone.
  - **Increased adoption of alternative materials:** A shift is considered from the conventional building blocks to alternative construction materials. The percentage share of autoclaved aerated concrete (AAC) blocks, hollow concrete blocks, and hollow clay blocks becomes predominant, while the other locally available materials such as compressed stabilised earth blocks (CSEBs) and laterite stone blocks remain as per the current trend. The transition to such less energy-intensive materials can reduce both embodied and operational emissions.

    - Installation of an insulation layer in the wall: Installing wall insulation becomes a standard practice in the construction of residential buildings, as it helps keep the indoor space more comfortable and leads to energy savings.

- **Green and energy-efficient commercial buildings:** Historically, the adoption of green buildings has varied across different categories of commercial buildings. Privately owned hotels and office buildings have seen major adoption, whereas unorganised retail and other service buildings have a lower adoption rate for green buildings. The low-carbon trajectory considers a 95%–100% adoption of green buildings by 2050 across all major commercial buildings. This yields an improved energy performance index for buildings that generate a 25%–30% savings in energy consumption, which keeps compounding over the years. This transition helps mitigate operational and embodied emissions with better building design and sustainable material choices.

- **Higher uptake of electric cooking:** More than 60% of households switch to electric cooking by 2040, eventually reaching 100% by 2070, with improved electrification. Replacing liquefied petroleum gas and other cooking fuels with electric cooking considerably improves energy efficiency and reduces the reliance on fossil fuels.

- **Use of green cement and steel for construction:** Construction materials such as cement and steel are sourced from production units with a lower carbon footprint. Green cement production utilises waste materials from other industries, and green steel is produced using hydrogen as fuel or other RE sources or even by recycling scrap steel, thereby reducing embodied emissions.

- **Phasing out diesel generators:** Buildings depend on diesel generators to provide back-up power in case of a grid outage. Currently, in Karnataka, approximately 3% of the annual domestic electricity demand and 11% of the annual commercial electricity demand is attributed to diesel generator sets. In the low-carbon pathway, to phase out fossil fuels, this dependency is reduced by ensuring robust grid management for uninterrupted energy supply to the connected load of buildings. This helps mitigate direct emissions from fuel consumption in diesel generator sets. Our assumption is that the entire load of diesel generator sets will be taken by the grid. Other cleaner fuel options include natural gas, energy storage solutions, and hydrogen fuel cells, all of which are yet to be widely adopted.

- **Installation of RTPV:** The integration of RTPV in residential and commercial buildings is regarded as a widespread trend, assuming that 20% of the total available roof space is considered usable for RTPV installation. This enables the installation of nearly 50 GW across the buildings sector—10 GW in commercial and 40 GW in residential (assuming continued policy push for residential RTPV uptake).

Figure 14 shows the operational electricity demand from residential buildings, indicating the impact of passive design strategies, electric cooking, and RTPV levers when applied in the order with respect to the reference scenario.

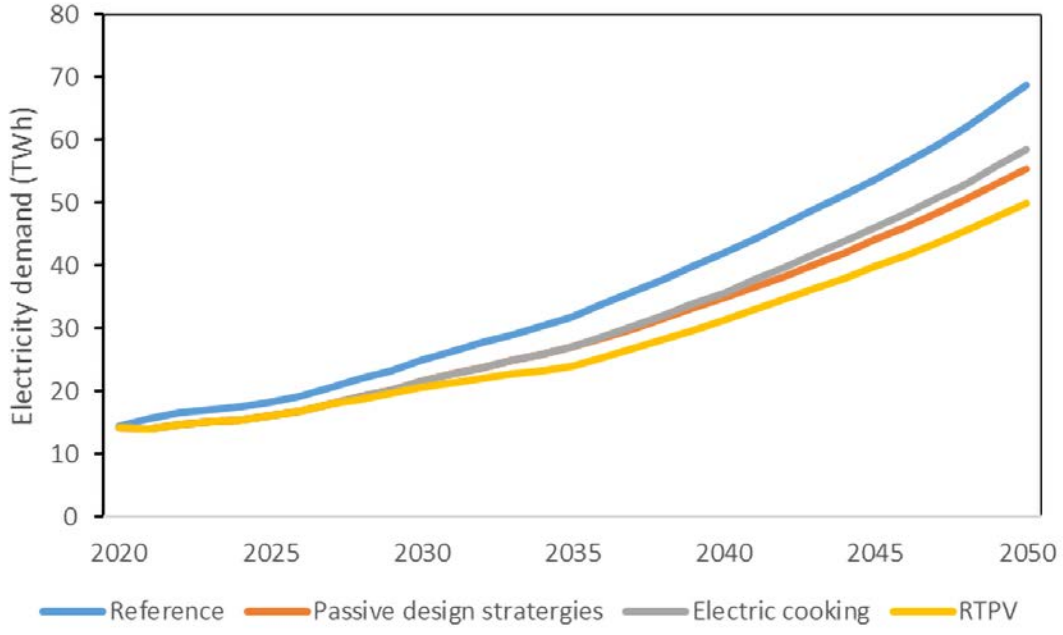


Figure 14: Operational electricity demand in the residential sector

Figure 15 illustrates the operational electricity demand in the commercial sector, highlighting that a 32% reduction can be achieved by 2050 through interventions such as adopting green building principles, avoiding reliance on diesel generators, and integrating RTPV systems in commercial buildings. The total emissions (including direct and indirect emissions) from the buildings sector are expected to reach almost 52 Mt CO_2e by 2050 under the reference scenario. As per the Intergovernmental Panel on Climate Change's emission inventory report, direct emissions from the buildings sector, mainly resulting from the burning of cooking fuels and the use of diesel for generators, only constitute a small fraction of the total emissions from the state. However, it is an integral sector that drives emissions via other sectors, e.g. the impact of electricity demand on the power sector and the use of construction materials from key industries such as steel, cement, and bricks. Figure 16 shows that direct emissions from both residential and commercial buildings can be reduced by nearly 50% compared with the reference scenario through interventions such as the adoption of electric cooking and the elimination of diesel generators by 2050.

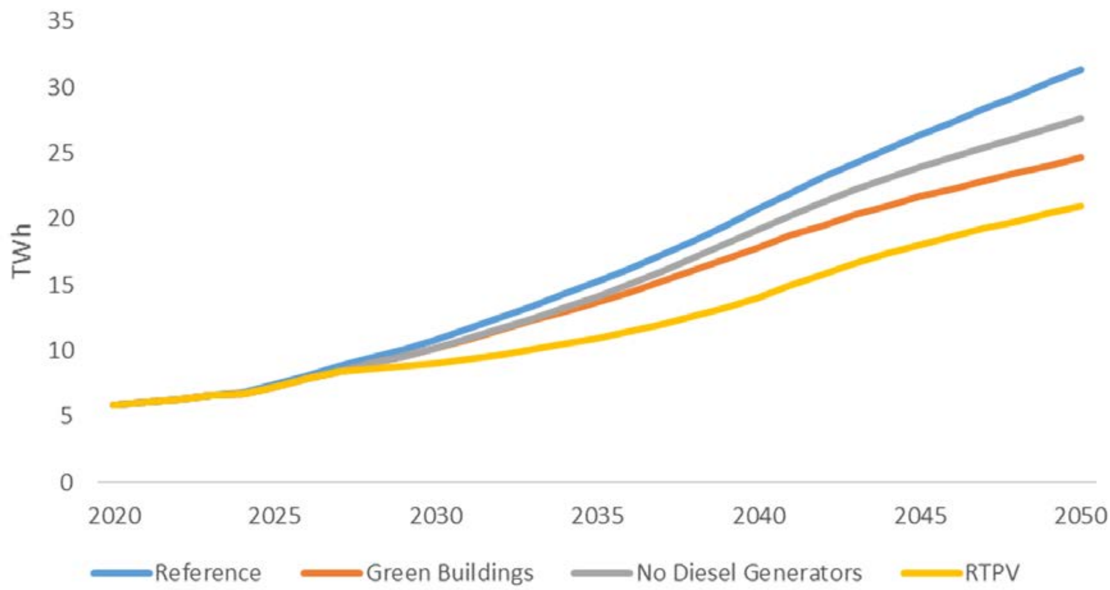


Figure 15: Operational electricity demand in the commercial sector

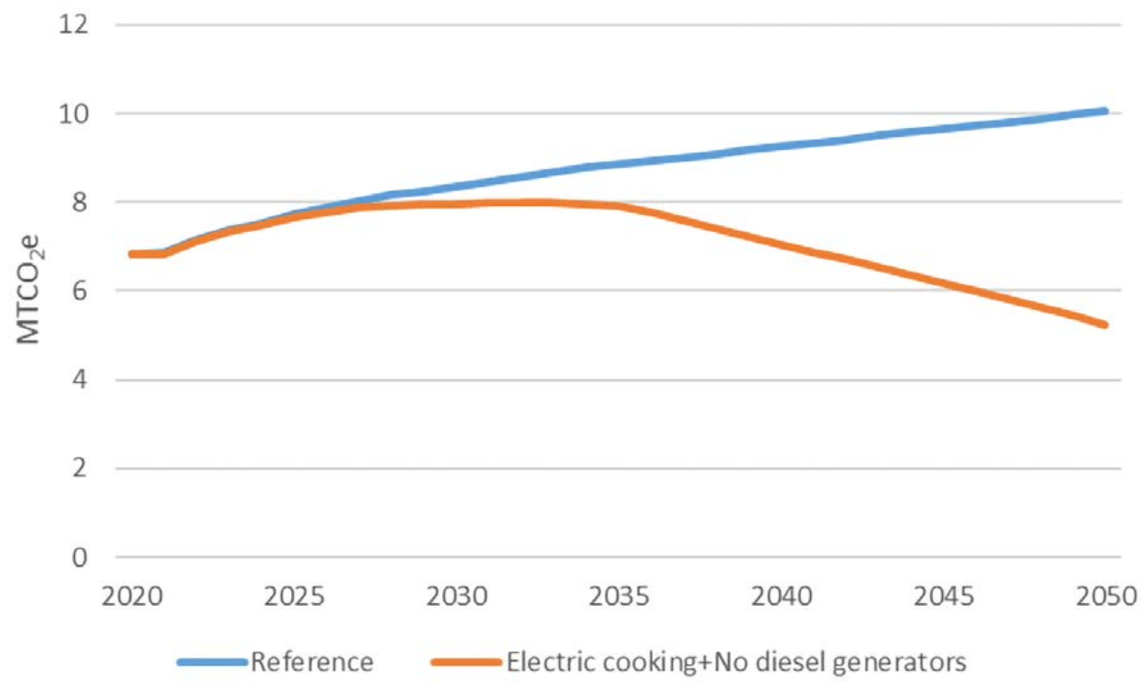


Figure 16: Direct emissions from the buildings sector

Investment vs Savings: Green commercial buildings

Green and energy-efficient buildings refer to a building structure that is environmentally responsible and resource-efficient throughout the lifecycle. The main reason for adopting such structures is to reduce the energy requirement. Various case studies and research demonstrate an annual savings of 25%–30% in the energy consumption of a single green building structure. This leads to hefty savings in electricity bills and compensates for the additional cost of construction over conventional buildings. The observed return on investment for a single project is around 4–5 years, depending on the occupant's conduct and the regular operation and maintenance of the building (UNDP, 2017).

The impact of energy savings at a sectoral level was analysed through *Namma* SAFARI, considering that the existing and upcoming building stock in each asset class supports the adoption of green buildings and each new building leads to 25%–30% savings over its entire life of at least 100 years. Figure 17 shows the results produced by the model at the sectoral level, indicating tremendous potential for annual energy savings each year.

Notably, the potential mitigation lever for the adoption of green commercial buildings will require additional investments in the buildings sector. In this study, the cost of conventional construction of commercial buildings was considered in the range of 2500–10,500 INR/sq ft for Bengaluru based on JLL's Construction Cost Guide, India, for various asset classes such as hotels, offices, hospitals, schools, and retail.

The incremental cost of construction to adopt green building strategies is nearly 5%, based on previous case studies on green and energy-efficient (UNDP, 2017). The Namma SAFARI model helps determine the impact of this incremental cost of construction across the entire built-up area of all asset classes modelled for commercial buildings. This provides a sectoral overview of investments needed in the buildings sector through the low-carbon roadmap, considering that all new buildings will follow an independent trajectory for the adoption of green buildings in the respective asset classes.

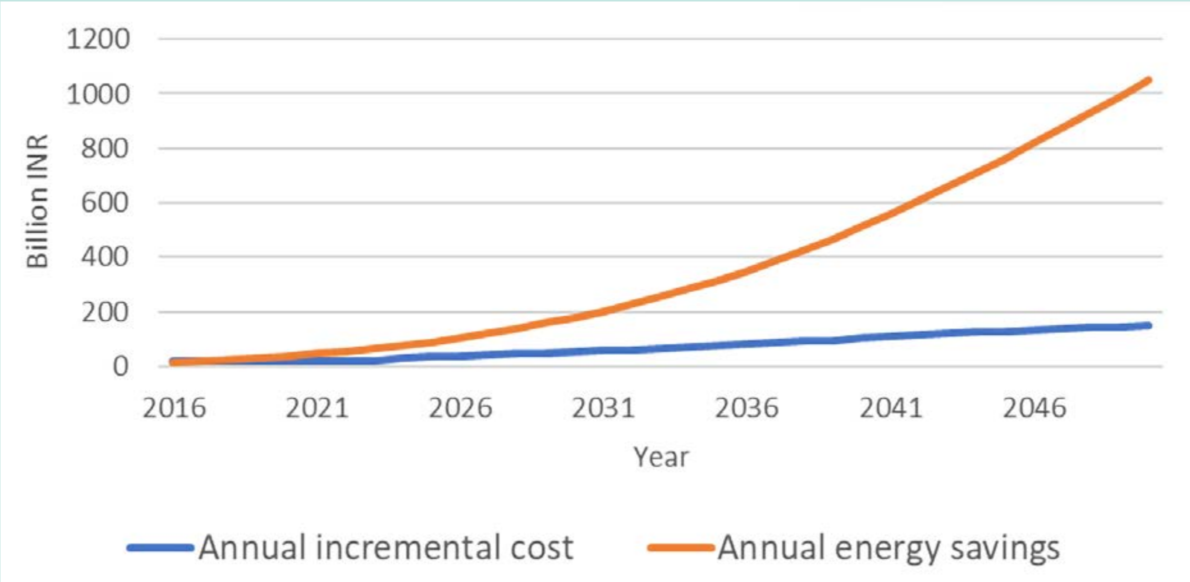


Figure 17: Annual incremental cost vs. annual energy savings

4.2. Co-benefits / Cross-sectoral impacts

Mitigation interventions in India's buildings sector, such as passive design, RTPV, cool roofs, and electric cooking, offer significant co-benefits beyond emission reduction. A low-carbon trajectory reduces the net grid electricity demand compared with that under the reference / current trajectory, thus reducing the pressure on the grid to cater to huge demands from the industry and transport sectors owing to a low-carbon transition in those sectors. This also lowers energy bills, improves indoor comfort, leads to better air quality, and enhances public health, particularly for women and children. Measures like RTPV adoption and passive cooling strategies can potentially reduce the strain on the power grid, support renewable energy integration, and create green jobs. Additionally, these measures contribute to urban heat mitigation, energy security, and increased resilience to climate extremes.

4.3. Key state policy focus for promoting green buildings (2025–2035)

The state could promote the use of sustainable materials in the construction industry. While alternative construction blocks such as AAC, hollow concrete blocks, and hollow clay blocks can be widely used in Karnataka, the adoption of localised materials including laterite blocks, CSEBs, and fly-ash blocks should be encouraged by the state. Developing an in-depth standard guideline for the use of such localised materials can help users make informed decisions. Materials should be selected according to the climate zone, with considerations of heat gain and embodied emissions.

As the state has already mandated compliance with Eco Niwas Samhita Karnataka (ENS-R) 2020, it is important to catalyse the wider audience to comply with the code. This can be tackled by increasing awareness of the long-term benefits of code compliance. The integration of ENS-R in various government housing schemes and urban planning policies can create a demand for green buildings in the residential space. Moreover, subsidising the initial capital cost of such buildings through a state policy can attract private developers.

With the state target of achieving 1 GW of RTPV installed capacity by 2027, along with a subsidy for RTPV given under the central scheme Pradhan Mantri Surya Ghar Muft Bijli Yojana, RTPV adoption could be accelerated in the state. Additionally, allowing net metering creates a conducive environment for more households to install RTPV on their rooftops. Generating energy from renewable sources can also support the shift towards electric cooking, which can significantly cut down direct emissions from the residential sector.

The state can consider developing a cool roof policy, as it is an easily actionable way to reduce the cooling electricity demand and emissions, especially in urban areas. This will also enhance indoor thermal comfort, thereby mitigating the impacts of urban heat island and improving public health, particularly pertinent with an increase in extreme heat under a changing climate.

Because energy building codes are mandatory in the state, introducing reward and recognition mechanisms can enhance code implementation and sustain energy efficiency post-construction. This can be achieved by linking the recognition of star-rated buildings with code-compliant buildings, following the verification of a building's energy performance.

The state should consider developing an action plan for zero-carbon buildings to support smart cities under the Climate-Smart Cities Assessment Framework (CSCAF). This plan should include strategies and actions to reduce embodied emissions from buildings, informed by the local context and involving transformative measures.


PRINCE
ON DUTY
CNG

5. Transport Sector

According to the Economic Survey of Karnataka 2023–2024, the services sector contributed to around 66% of the state's GDP in 2022–2023, 6% of which is attributed to the transportation sector, including road, rail, air, and water (Planning, Programme Monitoring and Statistics Department, 2024). If historical levels of growth are sustained for the next decade, further driven by population growth, urbanisation, and income rise, the demand for passenger and freight transport can be expected to grow at an annual average rate of 5% and 7%, respectively (Government of Karnataka & PwC, 2021).

From 2013 to 2024, the road transport sector of Karnataka experienced remarkable growth, with the number of registered vehicles nearly doubling from 16 million to 32 million (Bangalore Mirror, 2024). Notably, this surge was particularly pronounced in rural areas.

This study focused on key vehicle categories, including two-wheelers, three-wheelers, cars, buses, and freight vehicles of varying sizes—light-duty vehicles (LDV), medium-duty vehicles (MDV), and heavy-duty vehicles (HDV). A stock-and-flow model was developed to estimate the vehicle stock for each category during 2024. Model inputs include annual vehicle registration data from 2001 to 2024 for two-wheelers, three-wheelers, four-wheelers, buses, LDVs, MDVs, and HDVs, sourced from the VAHAN database (Ministry of Road Transport & Highways, Government of India, 2025). These new registrations were added to the existing vehicle stock. Vehicle retirement was estimated based on the average service life assumptions. For two-wheelers and three-wheelers, the average service life was considered to be 12 and 10 years, respectively. For vehicles with longer lifespans (i.e. cars, buses, LDVs, MDVs, and HDVs), the service life was divided into three phases: up to 10 years, 10–20 years, and beyond 20 years. Survival rates were assumed for each phase for every vehicle category. To capture uncertainty, a sensitivity analysis was conducted by varying the survival rates by ±5%, providing a range for the projected vehicle stock. The estimated number of on-road vehicles in Karnataka, based on this vehicle stock modelling, are provided in Table 1.

Table 1: Estimated stock values for different vehicle categories in Karnataka in 2024

Vehicle category	Stock (in million)
Two-wheeler	13.4 ± 2.2
Three-wheeler	0.316 ± 0.06
Car	3.04 ± 0.15
Bus	0.097 ± 0.009
Light-duty vehicle	0.549 ± 0.02
Medium- and heavy-duty vehicle	0.332 ± 0.03

Figure 18 (left panel) shows the share of each vehicle category in the total vehicle stock for 2024 and its share of emissions (right panel). Private vehicles, including two-wheelers and cars, make up the largest portion of the vehicle stock, followed by freight vehicles, buses, and three-wheelers.

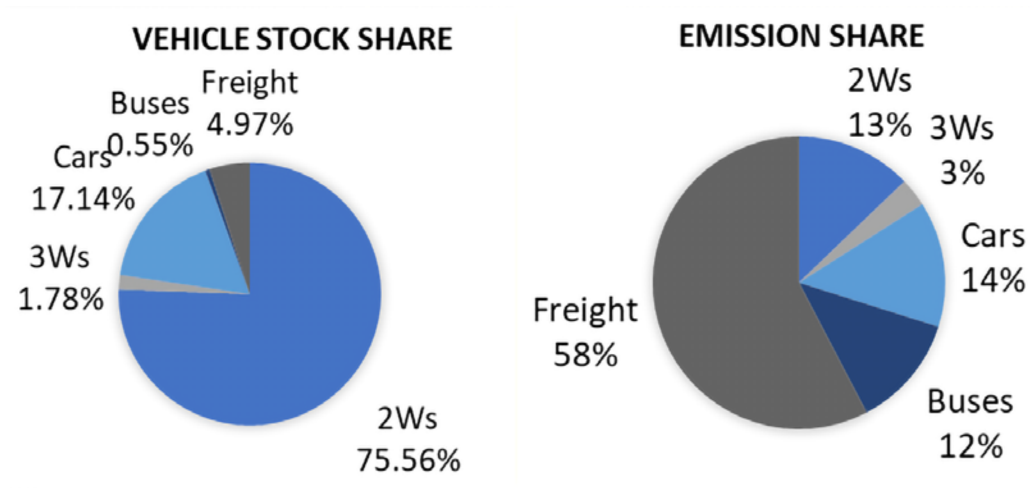


Figure 18: Share of each vehicle category and its emissions for 2024

This study estimates that the road transport sector, encompassing two-wheelers, three-wheelers, cars, buses, and freight vehicles, contributed ~25–30 $MtCO_2e$ in 2024. Vehicles with longer trip lengths, such as freight vehicles and buses, significantly impact road transport GHG emissions, regardless of their share in the total vehicle stock, as shown in Figure 18. In terms of the fuel-wise contributions to road transport GHG emissions, diesel remains the dominant source, responsible for 80.23% of emissions, followed by petrol at 19.76%.

5.1. Low-carbon trajectory

Figure 19 presents the annual direct emission trajectory of the road transport sector, illustrating the impact of sequentially applied interventions under the low-carbon scenario. In the absence of mitigation measures, emissions are projected to continue growing at the historical rate, reaching over 45 $MtCO_2e$ by 2050—an increase of 95% compared with 2020 levels. However, the implementation of key transport policy levers, such as enhanced fuel efficiency standards, electrification, and modal shifts in both passenger and freight transport, leads to a peak in emissions at 28 $MtCO_2e$ in 2025, followed by a steady decline. By 2050, these interventions result in a 73% reduction in GHG emissions compared with the reference scenario.

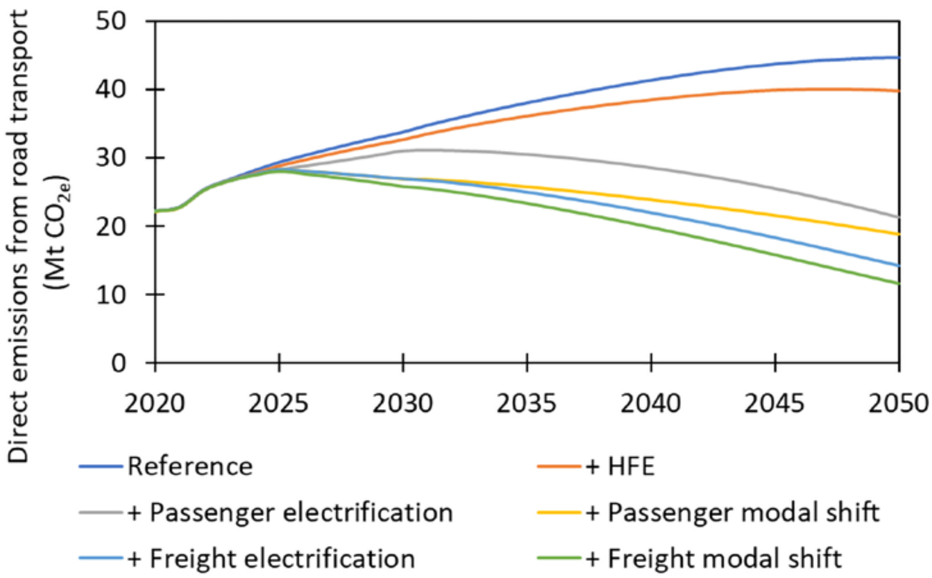


Figure 19: Annual direct (Scope 1) emissions from the transport sector

Figure 20 illustrates the annual electricity demand from the transport sector across different scenarios. In the reference scenario, electricity demand is projected to rise to over 28 TWh by 2050, representing a 92% increase from 2020 levels. Most interventions, such as electrification of passenger and freight transport and modal shifts toward electric public transport modes like metro systems and buses, lead to a significant increase in electricity demand.

- Improved fuel efficiency: This scenario assumes tightening of fuel economy and vehicle emission standards across vehicle segments, leading to improved fuel efficiency in the near to medium term. A 1.5%–2% annual improvement in efficiency is assumed across modes.
- Passenger modal shift: A key intervention is the shift in intercity passenger travel to rail-based modes. This could be driven by improvements in rail infrastructure, service quality, and targeted incentives. The share of rail in intercity transport demand is assumed to increase to 40% by 2050 compared with 20% in the reference scenario. Urban passenger transport is also assumed to significantly shift toward public transport modes, with metro and bus each assumed to service 35% of urban passenger demand by 2050. This is in contrast to the declining trend of public transport in the reference scenario and could be supported through investments in infrastructure, integration across modes, and improved last-mile connectivity.
- Freight modal shift: This scenario assumes a higher share of rail-based freight transport, increasing to 45% by 2050 compared with 25%–30% in the reference case. This shift is only possible with the successful implementation and scaling up of dedicated freight corridors and associated logistics infrastructure improvements.
- Electrification of passenger transport: Electrification plays a central role in long-term decarbonisation of the sector, and we assume aggressive electrification in the low-carbon scenario, such as full electrification of two-wheelers and 70%–90% for other passenger modes including three-wheelers, cars, and buses by 2050. This uptake is driven by increasing climate awareness, technology improvements, and cost parity with internal combustion engine (ICE) vehicles.
- Fuel shift in freight transport: The share of diesel-powered freight vehicles is assumed to reduce over time. In the LCV segment, this decline is steeper, and up to 50% LCVs are assumed to shift to electric vehicles by 2050. In contrast, the HCV segment continues to be dominated by diesel, with the CNG share increasing to 35% by 2050.

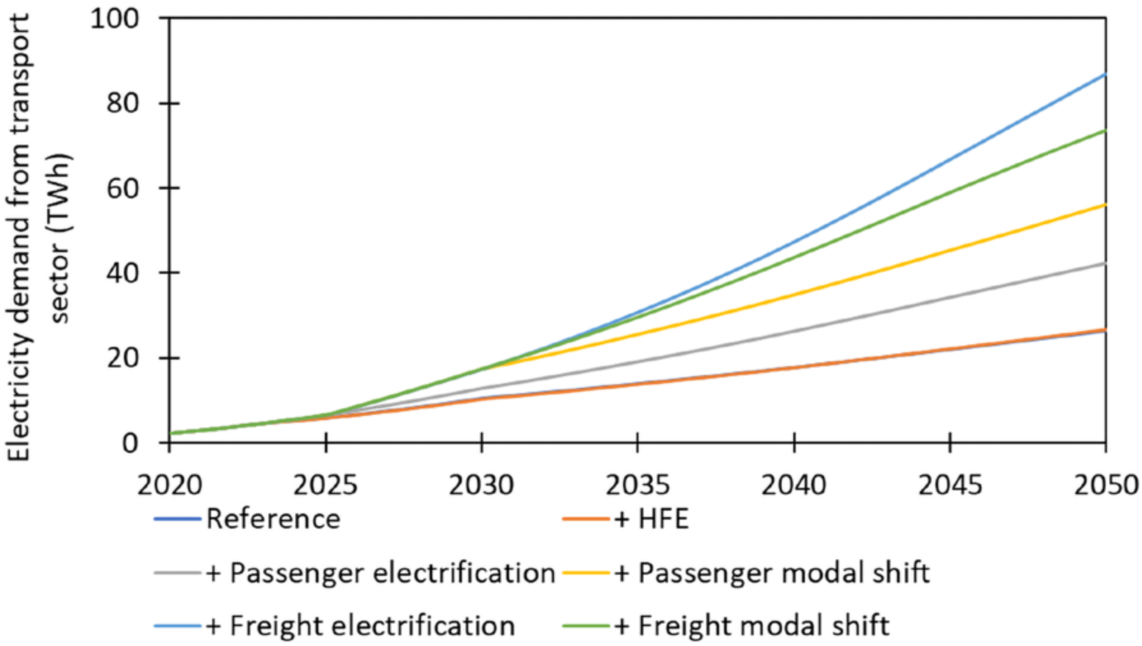


Figure 20: Annual electricity demand from the transport sector

5.2. Co-benefits / Cross-sectoral impacts

Impact on the power sector: The electrification of passenger and freight transport is expected to drive higher electricity demand from the power sector than that in the reference scenario. While electricity for transport constitutes a small share of the total electricity demand, it could pose challenges in peak demand or completely change the daily load profile.

Impact on state revenues: Incentives provided by the government for the purchase of EVs, such as road tax exemptions, reduced Goods and Services Tax rates, and upfront subsidies, may lead to an increased financial burden on state revenues. However, this potential loss can be offset through complementary measures such as promoting a modal shift from private vehicles to public transport including metro trains and intra-city buses. Increased ridership in public transport can enhance farebox revenue and reduce road maintenance costs due to lower traffic congestion. An additional co-benefit of EV adoption and switching to public transport is improved air quality due to reduced congestion on road and zero tailpipe emissions from EVs, leading to savings in healthcare costs.

5.3. Key state policy focus for shifting to green mobility (2025–2035)

- Incentivise modal shift of freight transport to rail, reaching 33% by 2030 (an increase from 27% currently), by offering tax rebates to companies using rail, funding last-mile connectivity, particularly to MSME clusters, etc.
- Strengthen last-mile connectivity to incentivise the use of public transportation to reduce air pollution and ease traffic congestion. The low-carbon scenario witnesses a rise in the modal share of public transport in urban Karnataka to 45%–50% by 2030.
- Implement scrappage policies to phase out older vehicles after their service life, as they have a lower fuel efficiency, and provide incentives for scrapping outdated vehicles.
- Accelerate EV adoption through purchase incentives, provide support for the expansion of charging infrastructure, and incentivise the establishment of battery manufacturing and recycling units, and promote the integration of renewable energy with EV charging to ensure a cleaner and more sustainable energy ecosystem.

6. Agriculture, Forestry, and Land Use (AFOLU) Sector

Karnataka's agriculture sector contributes to 15% of the state's GDP (Economic survey of Karnataka, 2023-24), and about 47% of the population depends on this sector for employment (FICCI, 2022). The sector is diversified, encompassing the cultivation of cereals, pulses, oilseeds, spices, horticultural crops, and plantation crops. Karnataka's Vision 2030 aims to enhance agricultural productivity and ensure food security by promoting sustainable farming practices and improving nutrition. Under this target, the state is committed to doubling agriculture productivity and farmer income in line with the national goal of doubling farmer income (Planning, Programme Monitoring and Statistics Department, Government of Karnataka, 2020).

The total agricultural land, which includes net sown cropland and total fallow land, currently occupies 60% of the state's total geographical area. Given the current growth rates of cultivation, the net cropland area gets saturated beyond 2043 owing to land constraints, as both total fallow land and cultivable/feasible wasteland are utilised for cultivation (Figure 21). With marginal yield improvement and land constraints, total food production of major crops also saturates by 2045, as seen in Figure 21 under the reference scenario.

In 2017, the state announced the Karnataka Organic Farming Policy, which emphasises the development of the entire organic value chain, from production to marketing (Government of Karnataka, 2017). This policy also aims to reduce the cost of cultivation, promote soil health, and ensure proper water management. However, only 1% of the total cultivated land is under organic cultivation. This is based on the cultivated area certified under organic farming policy in state (Government of Karnataka, 2017). To further support this initiative, Karnataka has implemented various promotional schemes, such as Savayava Bhagya Yojane, initiated in 2015, aimed at promoting organic farming at the Gram Panchayat level. Such policies not only help with increased soil health but also boost the soil sequestration potential of agricultural land.

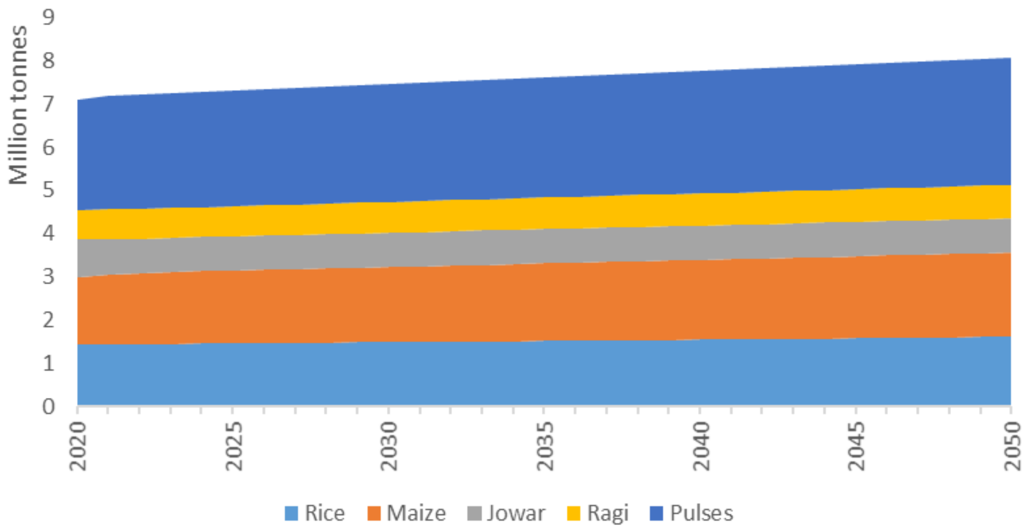


Figure 21: Annual production shares of various crops

A considerable portion of Karnataka's agricultural land is rainfed (35%), relying heavily on monsoon rains, making it vulnerable to climatic variability. Karnataka is a drought-prone state and has faced many water-related problems in the past. Projections indicate that Karnataka's total water demand will reach 1,397 thousand million cubic feet (TMC) by 2030, while the current sustainable supply is 761 TMC, possibly making growth in water-dependent sectors such as agriculture risky. Currently, only 7% of the net irrigated area is under micro-irrigation.

The land dynamics of the state under the reference scenario are given in Figure 22. As mentioned, agriculture is the major land use in the state. In terms of other land uses, Karnataka has an expansive forest cover (19% of the geographical area) and wasteland area (6% of the geographical area). In line with the Forest Conservation Act and the compensatory afforestation programme, historically, afforestation efforts have been greater than the forest clearance activities in the state, at an average of 71.7 thousand hectares annually. Continuing with similar efforts for afforestation, the forest cover in the state can grow till 2028, after which land constraints begin to show, and the land available for afforestation falls to 59 thousand hectares in 2029 and continues to decline at 7% annually till 2050. With these efforts, the forest cover reaches 3.87 million hectares (20% of the geographical area) by 2032. However, owing to continued forest clearance for developmental activities, based on historical data, the forest area starts declining despite afforestation efforts and reaches 3.4 million hectares by 2050. Wasteland, another important land class, acts as a source for various land-use conversions. Wasteland is seen as potential land for built-up land, afforestation, and conversion to cultivated cropland. However, not all wasteland is feasible for these purposes, and the demand from each of these other land classes depletes the wasteland at a rate of 30 thousand hectares annually, with 60 thousand hectares of wasteland remaining by 2050.

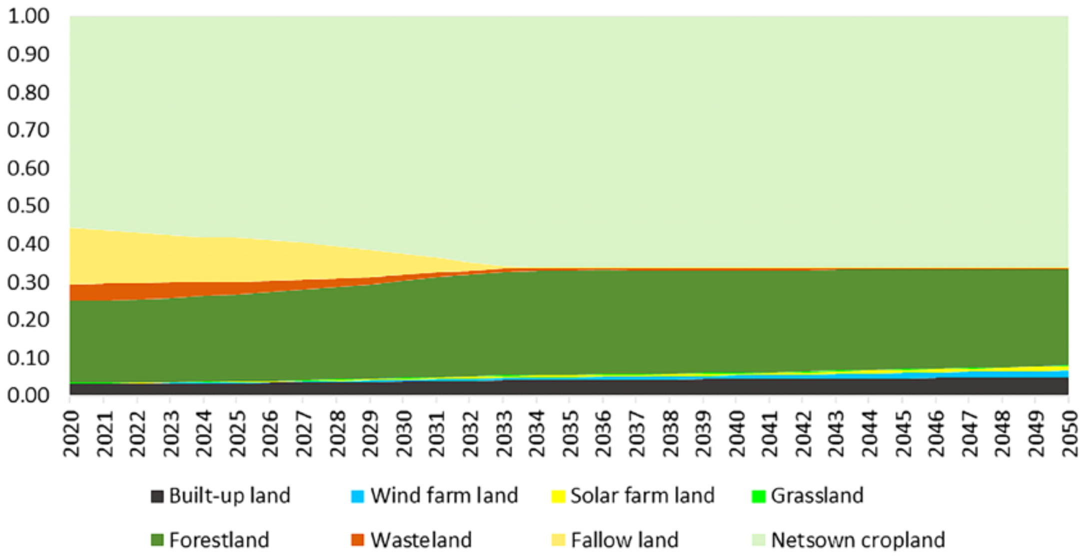


Figure 22: Land dynamics under the reference scenario

6.1. Low-carbon trajectory

The AFOLU sector is a net sink for the state of Karnataka, offsetting the total emissions of the state by 15.7% in 2018 (GHG Platform India, 2023). With respect to the emissions, 60% of the AFOLU emissions come from livestock, followed by 30% from fertiliser application and 10% from rice methane emissions. Karnataka's forestry sector has been a net sink since 2016. It is expected that Karnataka, a forest- and biodiversity-rich state, will contribute 112 million tonnes of additional CO_2e in 2030 towards the NDC target. With current efforts, the state exceeds this target by 64 MT in 2030.

The AFOLU sector continues to be a net sink under the reference scenario, with removals reaching 26.9 $MtCO_2e$ annually by 2070. To increase the sequestration potential of the sector and reduce emissions, a series of levers were considered in line with the state's targets for food security, including efficient water management in agriculture, reduced reliance on fertiliser, and increased efforts in afforestation. Overall, a total increase of 17% in the net sink is possible with these interventions by 2045, which reaches 80% by 2050. Agricultural interventions reduce the electricity demand by 67% by 2040 and 100% by 2050. The details and impacts of each lever are described below and in Figure 23 and Figure 24. Further, the land-use pattern for this scenario is provided in Figure 25.

- Increased millet production: Millets, including Ragi, Jowar, Bajra, and other small millets, consume less water than rice and thus require less irrigation. The area under millets increases over time from 1.68 million hectares in 2025 to 1.87 million hectares in 2030. Further, with average yield improvements, this intervention helps increase millet production by 1.6 times by 2050 and reduces the irrigation requirement, ultimately reducing emissions from the agriculture sector. Further details on millet production are provided in Box 1.

- Increasing area under micro-irrigation: With this intervention, the irrigation efficiency is improved. The area under micro-irrigation gradually increases from 7% in 2025 to 50% in 2040, reaching a maximum of 75% by 2050. This increases the irrigation efficiency and thus reduces the emissions further by 10% by 2040 and 16% by 2050.
- Increasing area under organic farming: Emissions from fertiliser usage contribute significantly to the emissions from the AFOLU sector. To mitigate these emissions, we gradually increased the gross area under organic farming, which reaches 25% by 2050, reducing fertiliser use by 31% by 2050. This further reduces the emissions by 29% in 2050.
- Increasing uptake of solar pumps for irrigation: The uptake of solar pumps for irrigation can have a significant impact on electricity requirement from the agriculture sector. The uptake increases from 2%–5% in 2025 to 100% electric pumps becoming solar pumps by 2050, completely bringing down the agriculture electricity demand.
- Increasing forest and tree cover: The forest sector continues to be a net sink for the AFOLU sector beyond the NDC target of 2030. To enhance forest and tree cover and boost the sector's sequestration potential after 2030, additional afforestation efforts were considered. However, owing to land constraints, as mentioned in the reference scenario, land for afforestation becomes limited. Nevertheless, an increased effort for tree cover expansion is also considered from 17.6 thousand hectares in 2030 to 35 thousand hectares by 2050. Overall, this enhances the net sink of the AFOLU sector.
-

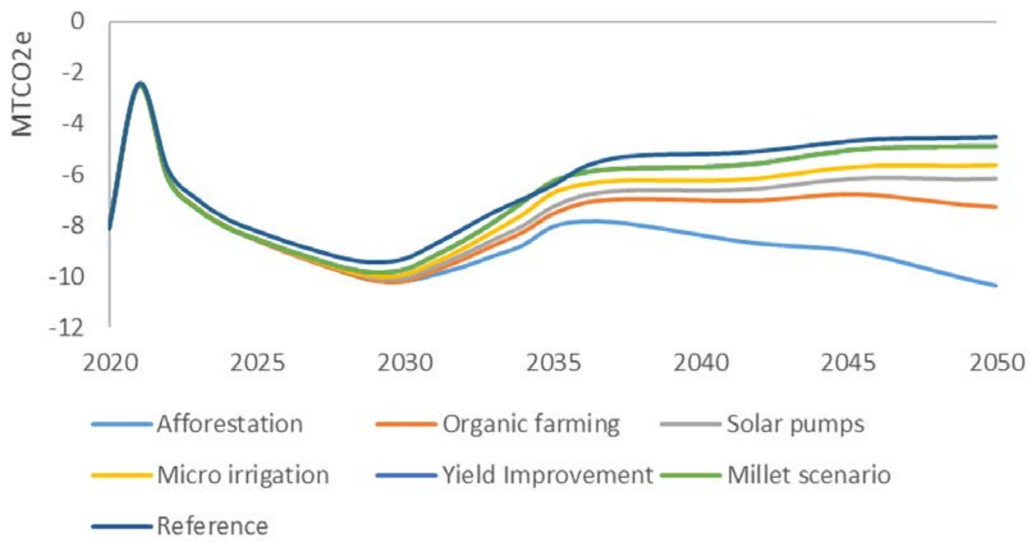


Figure 23: Direct emissions from the agriculture sector

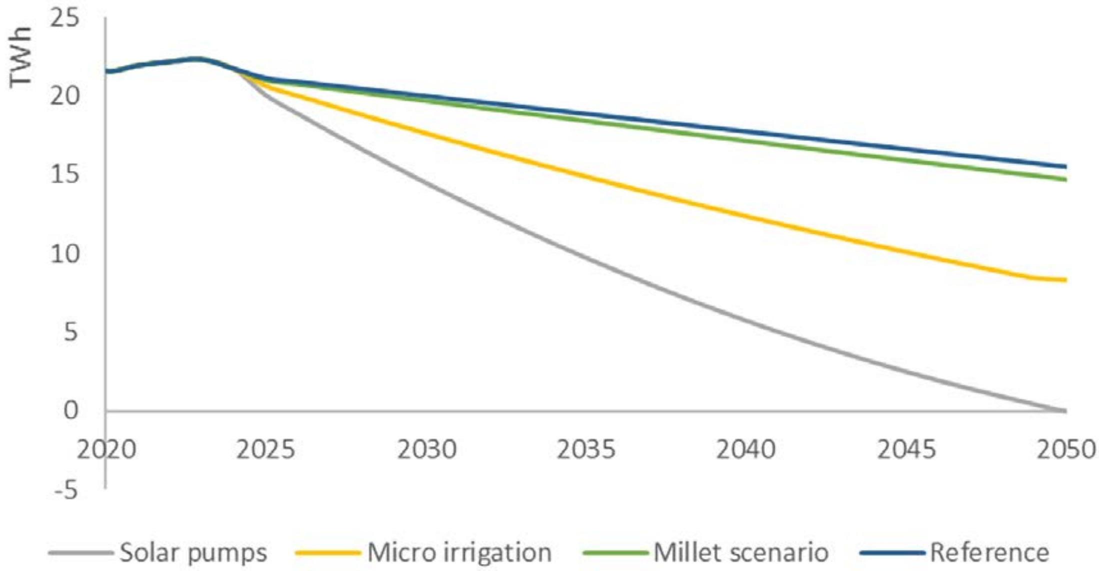


Figure 24: Annual electricity demand from the agriculture sector

Under the low-carbon scenario, with increasing land demand for net cropland expansion, afforestation, and RE expansion, wasteland depletion increases compared with the reference scenario (50 thousand hectares vs 30 thousand hectares annually). This leads to a complete depletion of wasteland by 2037, causing land constraints. With no land remaining for expansion, forest cover starts depleting, reaching 2.97 million hectares by 2050 (15% of the total geographical area).

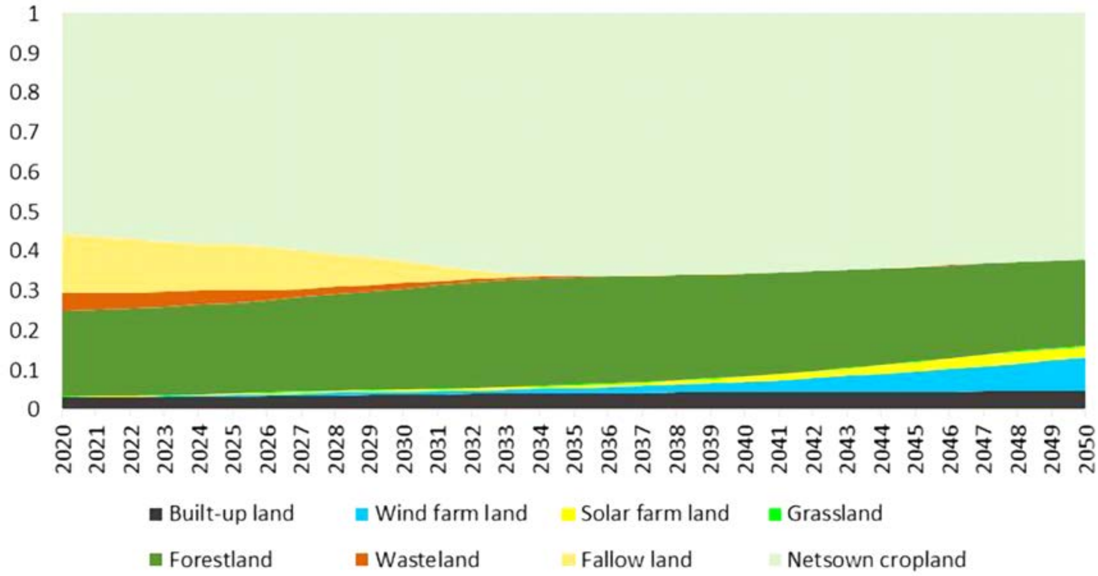


Figure 25: Land dynamics under the low-carbon scenario

Karnataka's contribution to the Millet Mission for India

Karnataka is a leading state in India for millet cultivation, often referred to as the 'Millet Bowl of India'. The state is well-known for producing millets such as ragi (finger millet), jowar (sorghum), and bajra (pearl millet). Karnataka contributes about 20% of India's total millet production, with a notable share in ragi (60%) and jowar (18%) production. The state has been at the forefront of promoting millet-based agriculture through various initiatives, including the Millet Mission, which aims to enhance both the production and consumption of millets. These efforts emphasise the nutritional and health benefits of millets. Additionally, with support from the government and private sector, Karnataka is developing its capabilities in millet processing and export, positioning itself as a hub for value-added millet products.

The Government of India has set an ambitious target to triple millet production from 15 million tonnes in 2021 to 45 million tonnes by 2030. Considering Karnataka's significant contribution to the national millet production, the state can set a target at 9 million tonnes by 2030. To achieve this, Karnataka is focusing on increasing the growth rate of millet production. In the 2024–2025 Kharif season, Karnataka has outlined ambitious plans for millet cultivation. The state aims to cultivate ragi on 0.73 million hectares, targeting a production of 1.176 MT. To encourage farmers, Karnataka provides a production incentive of INR 10,000 per hectare based on crop survey data. This initiative, part of the Raitha Siri Yojane launched in 2019–2020, has already benefited over 1,00,000 farmers, with financial support totalling INR 81.54 crore.

Under the millet scenario with an increased growth rate, Karnataka's millet production is expected to reach 3.37 MT by 2030, falling short by about 5.7 MT of the target. To bridge this gap, changes in cropping pattern and moving away from rice/wheat cropping patterns will be required.

Land for RE

Feasible wasteland available for RE expansion is acquired for solar by 2045 and for wind by 2040 under the low-carbon scenario. Beyond this, with the same land intensity, RE expansion requires land from agriculture and forest land. This eventually also creates a land-based risk to reach the projected wind and solar capacity. It is possible to generate 48.6 GW of solar and 49.9 GW of wind by 2040 and 139 GW of solar and 150 GW of wind by 2050, without any land constraints, which is lower than the projected capacity required. This highlights the importance of managing the electricity demand outlined under the net-zero scenarios described in this report. Thus, it is imperative to look at better land management policies, such as multi-land uses, and implement technologies that allow for lower land intensities (such as hub-heights and turbine wingspan).

6.2. Co-benefits / Cross-sectoral impacts

Karnataka is a drought-prone state. The low-carbon trajectory requires significantly lesser groundwater withdrawal, which means lesser subsidised electricity and savings for the state. Currently, around INR 14,000 crore is estimated as the total agriculture electricity subsidy, and if the low-carbon trajectory levels of micro-irrigation and efficiencies are achieved, an average reduction of 10% in the subsidy is possible from 2025 to 2035.

Studies on natural farming (NF) suggest that it has the potential to attract premium prices, supporting farmers undertaking this practice. This is especially seen in Karnataka. With NF, improved soil health can also contribute to long-term food security and enhance soil carbon capture, amplifying the mitigation benefits in the long term (Kumar et al., 2020; Kumar et al., 2024).

6.3. Key state policy focus for promoting sustainable agriculture

Reactivate the micro-irrigation policy: Reviving and operationalising Karnataka's micro-irrigation policy with crop-wise and season-specific targets will help enhance the water-use efficiency to support low-carbon agriculture. Clear hectare-wise coverage goals paired with climate commitments can drive the adoption and implementation of the policy. Moreover, studies have shown that adopting micro-irrigation results in a net increase in farmer incomes (Chandrakanth et al, 2013).

Solarisation of irrigation: Empowering farmers to become energy producers with an attractive feed-in tariff can help prevent perverse incentives that lead to the overexploitation of groundwater reserves to over exploit groundwater reserves. Grid planning will help accommodate additional solar power from agriculture.

Natural farming: In Karnataka, farmers have been practising NF for more than 15 years now; however, it has the downside of poor soil quality, if monocropping is practised. Incentivising the increase of cropping diversity and ensuring premium prices for such products can enhance the adoption of NF and contribute towards increasing farmer incomes.

7. Power Sector

Karnataka has nearly achieved self-sufficiency in power generation to meet the increasing demand. Occasional shortfalls caused by seasonal fluctuations in demand and supply are managed through short-term power purchases. Karnataka aims to further strengthen its power sector by leveraging its vast RE potential to drive a sustainable energy transition. The state plans to focus on cost-effective solar, wind, and hybrid systems with energy storage to ensure high reliability, flexibility, and round-the-clock supply. Through progressive policies such as the Karnataka Renewable Energy Policy 2022–2027, the state seeks to attract investments and promote green energy projects to maintain energy self-sufficiency and contribute to the NDC targets. Currently, the state's power generation capacity mix includes 5 GW of coal-powered thermal power, 3.6 GW of hydropower, 8 GW of solar power, and 5 GW of wind, in addition to power purchases from central generation stations. The electricity demand is set to grow by over three times by 2050 to meet the demands from all sectors under the reference scenario itself. To cater to this growing demand, the power generation mix of the reference scenario based on a least-cost logic was estimated.

In the reference scenario trajectory, the growth of RE in the short term is well-placed to meet the state's Renewable Purchase Obligation (RPO) targets and beyond by 2030. In the long term, by 2050, there is a significant growth in the non-fossil energy portfolio, with a solar capacity of 30 GW, wind capacity of 24.7 GW, PHS + RE capacity of 4 GW, and battery + RE capacity of 17.7 GW. However, with no additional assumptions on carbon cost/tax, there is continued reliance on cheaper coal power to meet the peak and baseload demand, with 25 GW of total thermal power capacity by 2050. Figure 26 shows the generation contribution from various resources in the energy mix. While the RE contribution increases and thermal power contribution reduces in the Central Generating Station (CGS) import over the years, coal (state and CGS) continues to be a major power source.

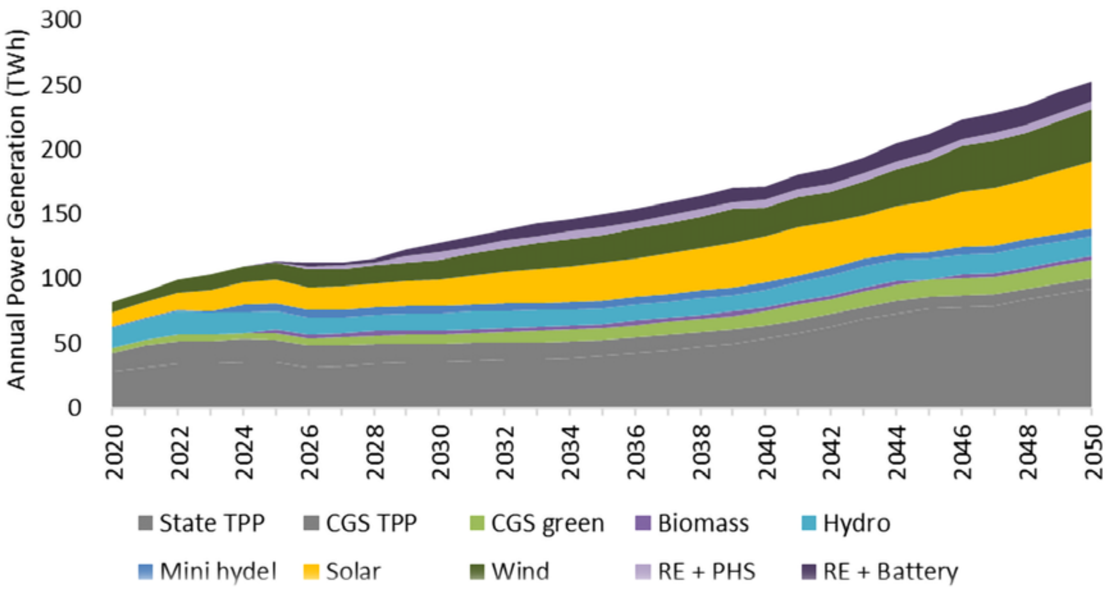


Figure 26: Expected power generation from various sources under the reference scenario

7.1. Low-carbon trajectory

A significant impetus for the electrification of various sectors, including transport, industry, and buildings (cooking), increases the electricity demand drastically under the low-carbon scenario since 2030. While the energy-use efficiency sees a remarkable improvement in all sectors, the drastic increase in electricity demand is not completely compensated. The electricity demand in 2050 under the low-carbon scenario is 408 TWh per annum, which is remarkably higher than the reference electricity demand of 237 TWh per annum (Figure 27a). The low-carbon scenario requires a substantial increase in power sector capacity addition.

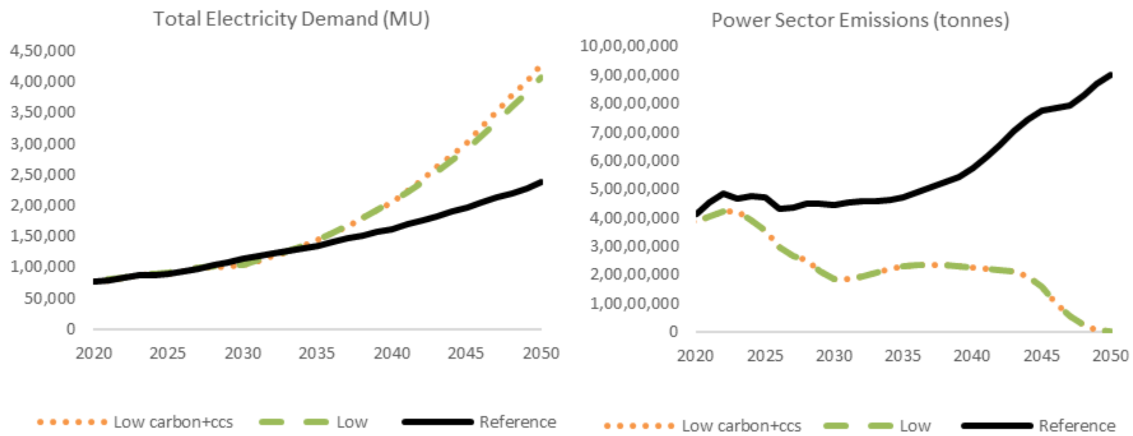


Figure 27: Comparison of (a) electricity demand and (b) associated emissions

Under the low-carbon scenario, we envisage that there will not be any new installation of state coal plants. This was also corroborated through our stakeholder consultation with KPTCL, as Karnataka is not endowed with coal reserves and transporting coal from mines in other states is becoming increasingly cost-intensive. With the gradual retirement of the existing state coal plants, the coal generation capacity in Karnataka becomes zero by 2050. An aggressive reduction in coal-generated electricity is also expected in the CGS energy mix, reducing the CGS thermal capacity contribution to the state to 36% of the total CGS import in the reference scenario itself. In the low-carbon scenario, we examined a scenario of energy self-sufficiency for Karnataka by 2050, gradually bringing the CGS imports to 0 by 2045. The large hydro capacity is also limited by the available geographical potential, and no new capacity additions were considered in this study.

Hence, the required major capacity increase mainly comes from solar, wind, pumped hydro storage with renewables (PHS + RE), and battery with renewables (Battery + RE). Our simulation indicates that by 2050, 133 GW of solar, 107 GW of wind, 8 GWh of PHS+RE, and 400 GWh of Battery + RE will be required to meet the electricity demand. Apart from the large solar installations, the excess generation from RTPV and solar pump sets also helps in meeting the electricity demand. The expected generation from these sources is depicted in Figure 28.

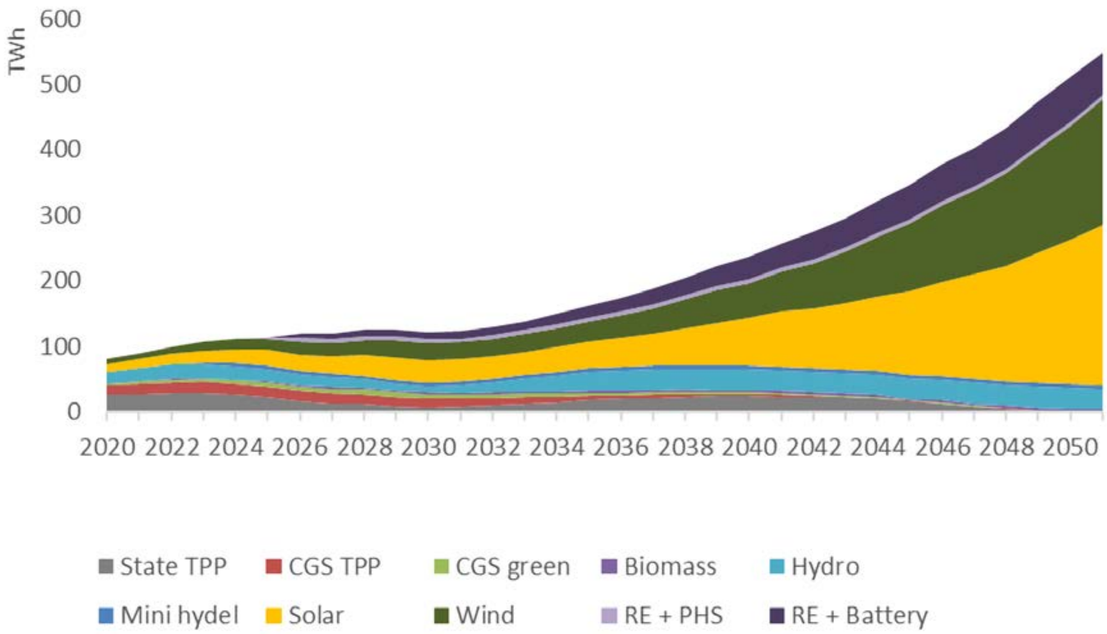


Figure 28: Expected power generation from various sources under the low-carbon scenario

The capacity addition is expected to require a cumulative investment of INR 3.1, 6.7, and 14 trillion during 2024–2030, 2030–2040, and 2040–2050, respectively. The investments required in the later decades are much larger than those under the reference scenario. Although the required renewable capacity addition is ambitious, with vast renewable potential available in the state, sufficient financial and policy support can help achieve the targets.

With a profound impact on the power sector, the low-carbon scenario drives the sectoral emissions to near-zero in 2050, compared with 90 Mt CO_2e under the reference scenario (Figure 27b). Large renewable installations help Karnataka achieve the RPOs declared till 2030, and the state expects to have excess renewable generation beyond the RPO requirement in the future. This unlocks the possibility of selling this renewable generation beyond RPOs to other states.

7.1.1. Low-carbon + carbon capture and storage (CCS) trajectory

The low-carbon + CCS scenario has a CCS facility that becomes operational gradually from 2040 to balance the CO_2 emissions from hard-to-abate sectors, such as industry, apart from following the low-carbon trajectory. The operational electricity supply requirements for the CCS unit progressively increase the total electricity demand starting from 2040 compared with the low-carbon scenario. The total electricity demand under the low-carbon + CCS scenario by 2050 will be 428 TWh per annum, which is 4% higher than that in the low-carbon scenario (Figure 27a). To meet this electricity demand by utilising low-carbon resources, additional renewable capacity would be necessary. Meeting the electricity demand in 2050 under the low-carbon + CCS scenario would require a slightly larger installed capacity (148 GW of solar, 115 GW of wind, 8 GWh of PHS+RE, and 424 GWh of Battery + RE) than that in the low-carbon scenario. The associated generation values are shown in Figure 29. Starting from 2040–2050, when the CCS starts getting added to the system, a larger investment (approximately 1 trillion more than the investment required in the low-carbon scenario) will be required in the power sector to meet the additional electricity requirement.

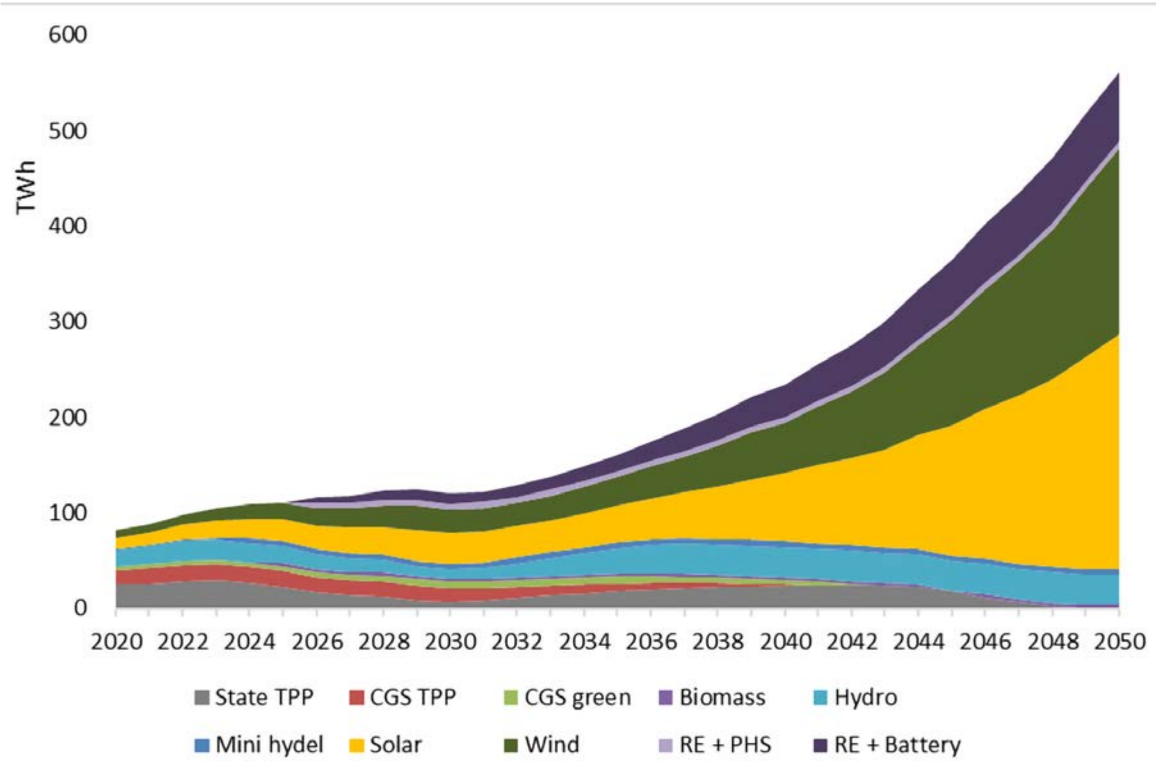
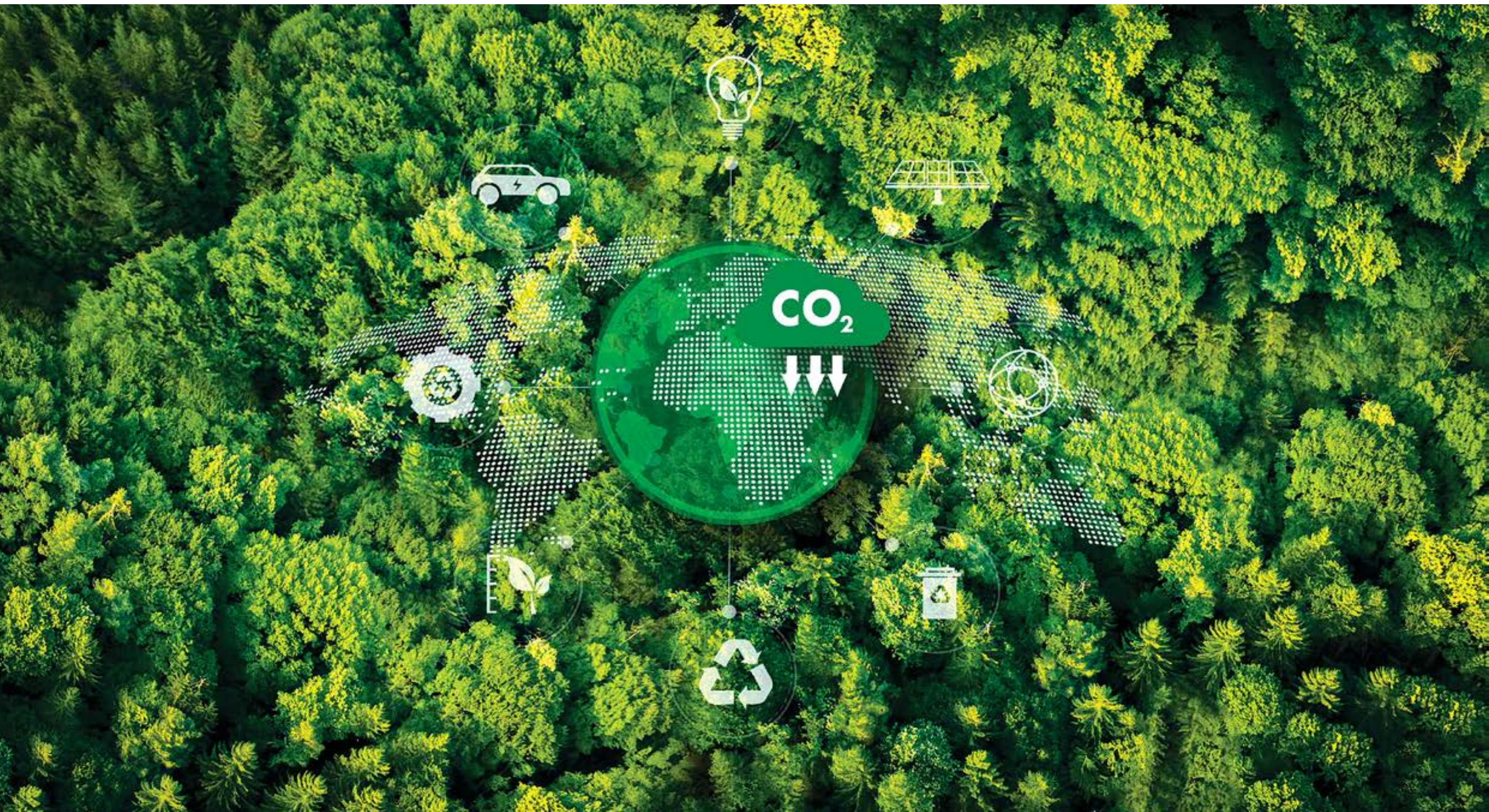


Figure 29: Expected power generation from various sources under the low-carbon + CCS scenario



To further investigate the possible issues because of increasing variability in the power supply due to RE, we analysed the SAFARI power sector results using R code. The code was designed to simulate the hourly demand and generation for a given year based on scenario-specific annual power sector results from SAFARI (solar, wind, coal, gas, nuclear, hydro, and storage capacity and generation). Coal and nuclear sources were assumed to be baseload/fixed generation, whereas gas, hydro, and storage were assumed to be flexible generation. The profiles for solar irradiance and wind speed at a hub height (100-m above ground) were obtained from the ERA5 database (Hersbach et al., 2023). The energy generation from solar and wind was estimated using the solar panel datasheet and the turbine power curve provided by manufacturers. Further, the hourly electricity demand profile was based on the KPTCL dataset for 2023 (Download Daily Load Curve, 2022). A comparison of the hourly demand–supply profiles enabled us to detect any mismatches, such as unmet demand and curtailed generation in a given year. Despite various uncertainties involved in the supply and demand profiles, the simulation results can be seen as a crucial indicator for assessing the scenario-specific, hourly scale supply–demand balance.

By 2050, with the gradual decarbonisation of the electricity grid in the low-carbon scenario, the R-based model indicates an hourly unmet demand (5% at the aggregate level), particularly during summer (Figure 30). Unmet demand can have huge implications for all sectors. However, there would also be excess generation at certain times (29%–33% at the aggregate level). In such a scenario, the excess generation can be stored and used to address the deficits at other time. This would require further installation of bulk electricity storage to reserve electricity at different time scales (hourly as well as seasonal). Demand pattern also plays an important role in the analysis. Owing to several uncertainties involved in predicting the hourly electricity demand pattern at a long timescale, we retained the same demand pattern of 2023 for this analysis. Any major behavioural intervention that changes the electricity consumption pattern or demand side management would impact the findings. Figure 30 shows a typical time series (7 days) during the summer of 2050 (high demand period) and monsoon of 2050 (low demand, high RE generation period) for the low-carbon scenario.

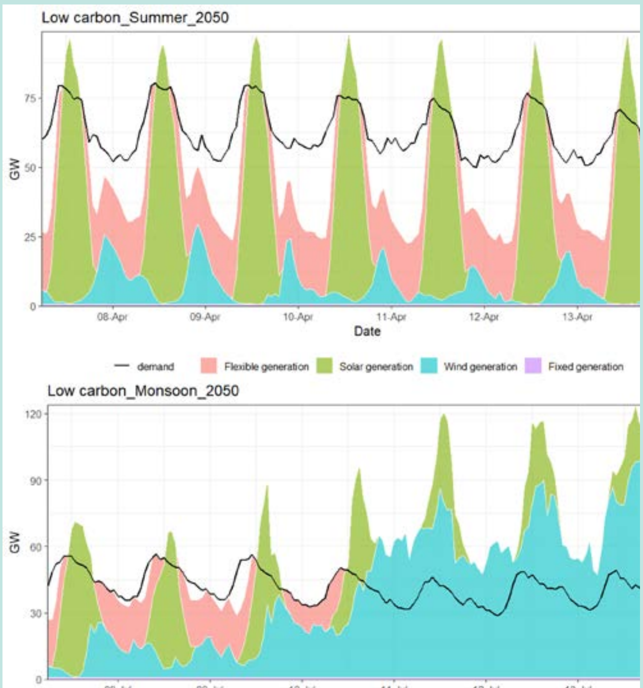


Figure 30: Typical time series (7 days) in a) summer 2070 (high demand period) and b) monsoon 2070 (low demand high RE generation period) for low-carbon scenario

	Year	Curt%	Unmet%
BAU	2050	5	1
Low Carbon	2050	29	5
Low Carbon + CCS	2050	33	5


CO2

8. Integrated Low-Carbon Development Roadmap for Karnataka

The previous sections presented detailed mitigation pathways for key sectors (industry, buildings, transport, agriculture, forestry, and power) and the impact of specific levers, as well as their co-benefits and cross-sectoral impacts. Figure 31 shows the integrated scenarios across the sectoral trajectories representing the combined effect on economy-wide emissions for Karnataka.

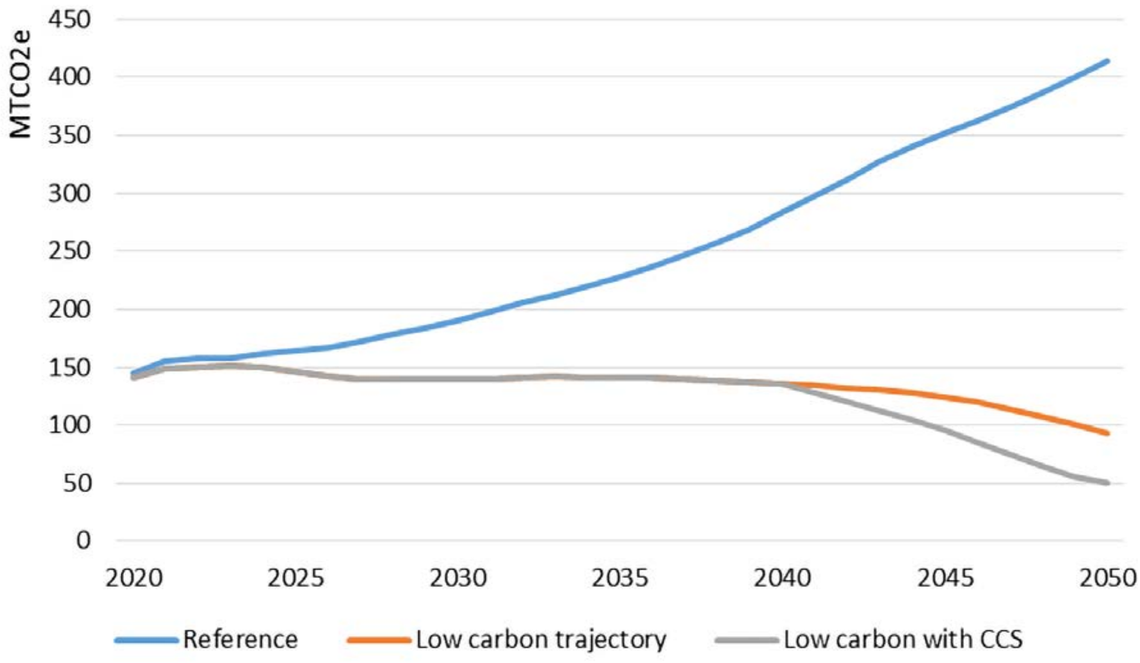


Figure 31: Annual GHG emissions across scenarios

Under the reference scenario, all major sectors experience a significant emission increase, driven by rising demand and limited structural change to enable climate action. However, the low-carbon scenario demonstrates that strategic interventions can not only curb emissions growth but also reverse trajectories in several sectors. Figure 32 provides the sectoral electricity demand and emission profile for Karnataka from 2015 to 2050. The industry sector sees the highest emissions growth in the Reference scenario, increasing by nearly 1.7 times in 2050 (with reference to emissions in 2025), continuing to be the most important driver of the state's future emissions. Under the low-carbon scenario, industrial emissions decline by 67% in 2050 (with reference to 2025), enabled by the different interventions discussed in detail in the industry section. Transport emissions grow by 52% in the Reference scenario because of rising freight and private mobility, but targeted interventions such as modal shifts and EV adoption reduce these emissions by 42% in 2050 (with reference to 2025) in the low-carbon scenario.

Across both scenarios, electricity demand rises significantly in end-use sectors. In the reference scenario, demand increases across buildings, transport, agriculture, and industry, driven by rising incomes, urbanisation, and economic growth. The industrial sector contributes around 84 TWh of the electricity demand by 2050, while buildings (residential + commercial) account for ~100 TWh. The transport sector's contribution reaches 26 TWh, and agriculture contributes around 15 TWh. In the low-carbon scenario, electrification deepens across all sectors. By 2050, the industrial sector's electricity demand increases by more than three times to reach ~278 TWh, while the buildings sector's demand reduces to reach ~69 TWh (combining 53 TWh residential and 16 TWh commercial demand) owing to passive cooling and RTPV uptake. Transport electricity demand doubles to ~54.5 TWh, reflecting full-scale electrification across modes. Notably, the agriculture sector's electricity demand drops to zero, reflecting the full adoption of off-grid solar irrigation. These trends highlight electricity as the foundation of decarbonisation—reinforcing the need for a clean, reliable, and flexible power system that can meet growing, shifted loads across sectors.

With a full shift to renewables and storage, power sector emissions drop to near zero in the low-carbon scenario, even as demand from electrified sectors rises. While this transformation is critical to enabling decarbonisation in end-use sectors such as buildings, industry, and transport, as discussed in the land-use section, there could be land acquisition risks that must be accounted for.

The AFOLU sector becomes a major carbon sink under the low-carbon scenario, with net sequestration improving by 14% as a result of continued efforts in afforestation and NF. In the buildings sector, direct emissions due to cooking rise modestly under the reference scenario (64%) but fall by 54% in the low-carbon scenario in 2050 due to the assumptions of electrification for cooking in urban households.

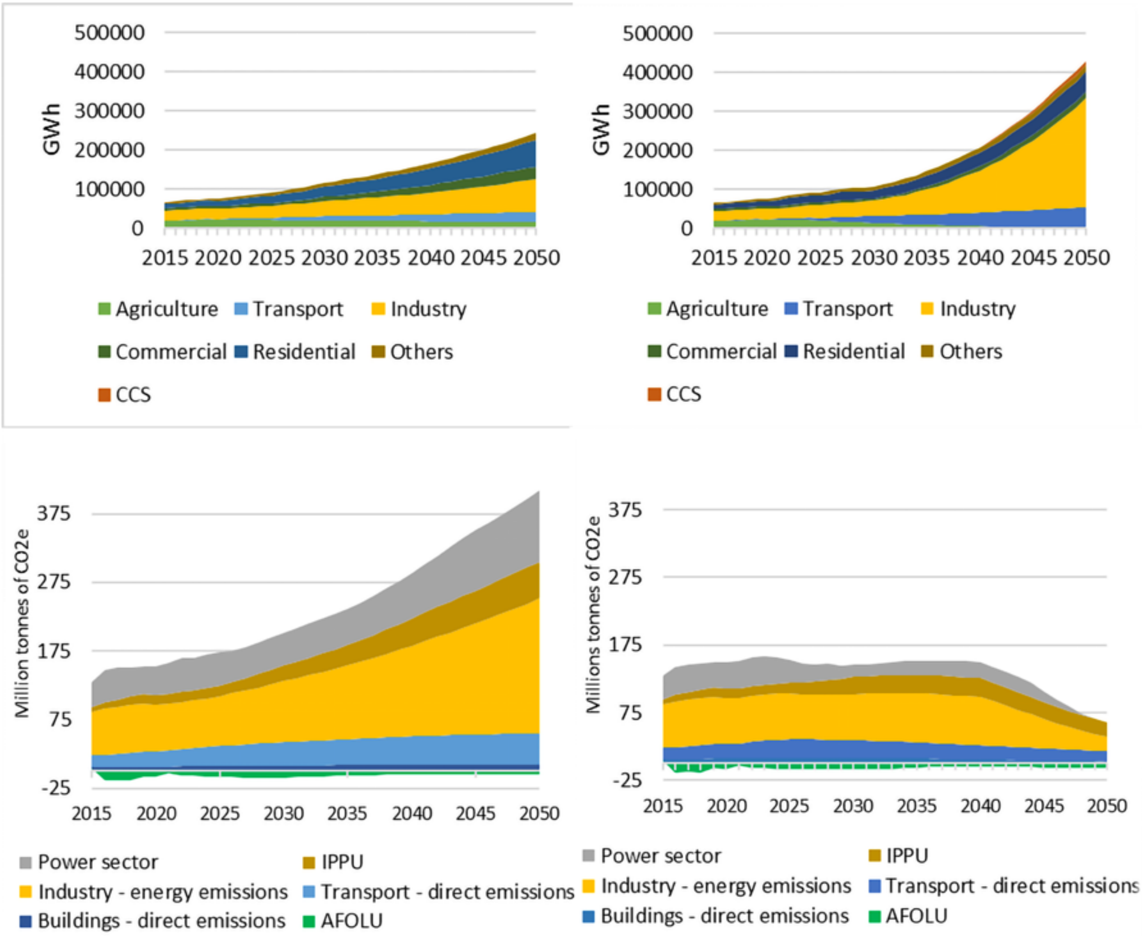


Figure 32: Sectoral electricity demand and sectoral emissions profile under reference and low carbon (with CCS) scenarios for Karnataka

The integrated analysis highlights the need for simultaneous action across sectors to achieve deep decarbonisation. The decarbonisation of the power sector emerges as a key enabler for emission reduction across transport, buildings, and industry, reinforcing the importance of early and consistent investment in RE. Demand-side measures, including modal shifts and improvements in energy efficiency, also play a critical role by reducing the overall energy demand and helping avoid long-term lock-in into carbon-intensive systems.

Importantly, the scenario assumes that such transitions are enabled by policy support. Such an integrated assessment provides a basis for identifying priority areas for intervention, sequencing actions, and supporting a sustainable clean energy transition for Karnataka.

To translate the long-term decarbonisation pathways into actionable strategies, the analysis identified a set of near-term policy focus areas for each sector in Karnataka. These are aligned with the integrated low-carbon and net-zero scenarios and are intended to inform implementation efforts within the current planning horizon. Table 2 outlines key short-term policy themes, the corresponding state departments for implementation or regulation, and relevant central government schemes or policies that Karnataka can leverage for financial and technical support. Additionally, it proposes indicators to track the progress and 2030 milestones aligned with the mitigation trajectory. This framework aims to support integrated, state-level planning and helps align short-term policy actions with long-term climate goals.

Table 2: Key State and Central Government policies relevant to Karnataka

Sector	Key state policy focus (short term)	Corresponding departments	Central schemes / policies	Indicator	Target/milestone for 2030(towards the low-carbon representative scenario)
Industry	State green hydrogen policy	Industry, KREDL, DISCOM	Green Hydrogen Mission	Hydrogen production and electrolyser capacity	280 kilo tonnes and 196 MW electrolyser capacity
	Green procurement - steel	Public procurement tender process - all departments	Green Public Procurement Policy (proposed by Ministry of Steel)	Share of green steel of total steel procured annually	37% (average emissions intensity of steel industry = 1.99 tCO_2e/ tfs = 4 star rated as per green taxonomy)
	Green procurement – cement	Public procurement tender process - all departments	–	Share of green cement of total steel procured annually	25%(average emissions intensity of the industry = 0.53 tCO_2e/ tonne)
	Incentives to shift to grid electricity	DISCOM	Green Energy Open Access regulations	Captively generated electricity using coal	7 TWh (in 2021, the total captive generation using coal was 11.5 TWh as per CEA)
	Scrap recycling infrastructure / supply chain - registered vehicle scrapping facilities	RTO	EPR - draft regulation	Scrap availability (% of scrap demand for steel)	1.3 million tonnes (sufficient to 33% of the total demand for scrap)
	Municipal solid waste management and setting up material recovery facilities	Municipalities / Urban Local Bodies (ULBs) / Pollution Control Boards	Solid Waste Management Rules	RDF availability	1.2 million tonne (assuming average NCV 16.6 GJ/tonne)

Sector	Key state policy focus (short term)	Corresponding departments	Central schemes / policies	Indicator	Target/milestone for 2030(towards the low-carbon representative scenario)
Buildings	Effective ENS implementation	Housing board and Rajiv Gandhi Housing Corporation Limited (for houses built under state schemes and PMAY); Urban development department - building bylaws, ULBs and town planning (implementation); KREDL	National Mission on Sustainable Habitat (NMSH) - implemented through three MoHUA flagship missions / programmes - AMRUT, smart cities and Swachh Bharat Mission	Sustainable residential buildings built-up area (additional from 2025 onwards)	166 million sq m (urban)
	Effective ECBC implementation	Urban development department - building bylaws; Urban local bodies and town planning (implementation); KREDL	–	Sustainable commercial buildings built-up area - (additional from 2025 onwards)	929 million sq m
	Incentivise RTPV adoption in commercial and residential buildings	KREDL, DISCOMS	Pradhan Mantri Surya Ghar Muft Bijli Yojana (PMSGMBY)	Installed RTPV capacity	1.5 GW - commercial 4.5 GW - residential

Sector	Key state policy focus (short term)	Corresponding departments	Central schemes / policies	Indicator	Target/milestone for 2030(towards the low-carbon representative scenario)
Transport	Incentivise public transport	Directorate of Urban Land Transport (DULT)	Smart cities mission, urban transport under AMRUT	Public transport modal share - urban	50%
	Incentivise freight transport via rail	–	PM Gati Shakti, freight incentive schemes of Indian railways, dedicated freight corridors	Rail modal share of freight transport	33%
Agriculture	Micro-irrigation coverage	Agriculture department	Per drop more crop (PMKSY)	Hectares under MI	5.3 million
	Solar-powered IP sets	KREDL, Agriculture department, DISCOMS	PM KUSUM	Solar capacity for agriculture	10 GW (PM KUSUM components B and C)
Forestry	Afforestation	State forestry department	National forest policy	Area under forest cover	25%
	Contributing to NDC targets	State forestry department	NDC target for additional sink	Carbon sink ($MtCO_2e$)	176
Power	Increase RE	KERC	Ministry of power RPO target	% generation met with RE	43%
	Increase energy storage systems	KERC	ESO national target (indicative)	% RE with storage	25%

8.1. Limitations and way forward

While the *Namma* SAFARI model can simulate the emission trajectories over the years depending on the sectoral mitigation levers, a certain level of uncertainty is involved. This uncertainty arises from disruptive technological innovation and future external events that are likely to occur across all sectors, with implications for the total emission trajectories.

- With respect to the transport sector, the model does not account for inter state vehicle movement (both passenger and freight) and the associated fuel consumption from vehicles registered in other states.
- The power sector transmission cost is estimated based on the assumption that the construction of an evacuation system for non-fossil-based capacity costs INR 1,000 crore/GW. Further, a granular assessment would entail detailed RE site specifications and could increase the uncertainty.
- The waste sector, although a small contributor to the overall emissions, will be part of our future work.

The scenarios presented in this report are not forecasts or definitive pathways but illustrative use cases that demonstrate the analytical capabilities of the *Namma* SAFARI model. They are constructed using a systems approach to capture dynamic interactions across sectors and reflect policy-relevant levers aligned with Karnataka's development priorities. These scenarios are intended to exemplify how the model can be used to explore sectoral transitions, quantify co-benefits, and assess the implications of long-term planning choices. The results serve to highlight the potential of the tool as a decision-support framework—one that complements existing departmental planning processes by enabling integrated analysis across emissions, energy, land, and economic indicators.

The tool is not prescriptive by design. Instead, it is built as a flexible and iterative platform that can evolve with stakeholder inputs, sector-specific data, and emerging policy priorities. Given the growing emphasis on performance-linked financing, climate-aligned development schemes, and sub-national contributions to national climate commitments, a model of this nature positions the state to engage more strategically with both central and multilateral actors. High-level engagement with senior government stakeholders indicates a strong institutional interest in applying this framework to ongoing and future planning exercises. Moving forward, the focus will be on deepening departmental integration, refining sector-specific modules, and operationalising the tool as part of Karnataka's long-term low-carbon development strategy.

9. References

Adekunle, S. K. (2024). Carbon sequestration potential of cement kiln dust: Mechanisms, methodologies, and applications. *Journal of Cleaner Production*, 446, 141283. https://doi.org/10.1016/j.jclepro.2024.141283

Banglore Mirror. (2024). *Vehicle sales triple in Karnataka; rural areas matching tren*. https://bangaloremirror.indiatimes.com/bangalore/others/bm-finance-fundas-2-upi-changes-auto-top-up-transaction-limit-hike/articleshow/114925885.cms

Bureau of Energy Efficiency & Alliance for an Energy Efficient Economy. (2024). *State Energy Efficiency Index* 2023. https://stateenergyefficiencyindex.in/wp-content/uploads/2024/02/seei-2023-report.pdf

Commerce & Industries Department. (2017). *Karnataka Electric Vehicle & Energy Storage Policy-2017*. https://wordpress.missionstartupkarnataka.org/wp-content/uploads/2022/12/Karnataka-Electric-Vechicle-and-Energy-Storage-Policy-2017-1.pdf

CSTEP. (2021). *Energy and emissions implications for a desired quality of life in India via SAFARI*. https://cstep.in/drupal/sites/default/files/2021-07/CSTEP_SAFARI_Final_Report_July2021.pdf

Deloitte. (2024). *Karnataka: Powering India's growth*. https://www2.deloitte.com/content/dam/Deloitte/in/Documents/about-deloitte/in-ad-india-karnataka-investment-destination-noexp.pdf

EMPRI. (2021). *Karnataka State Action Plan on Climate Change*. https://empri.karnataka.gov.in/storage/pdf-files/CCC/KSAPCC%20.pdf

Energy Department & Government of Karnataka. (2022). *Karnataka Renewable Energy Policy 2022-2027*. https://kredl.karnataka.gov.in/storage/pdf-files/ECREGIONALWRKSHP/Karnataka%20Renewable%20Energy%20Policy%202022-27.pdf

GHG Platform India. (2023). https://www.ghgplatform-india.org/afolu-sector/#

Government of Karnataka. (2017). Organic farming policy—2017. Government of Karnataka. http://organics-millets.in/assets/pdf/Organic-Policy-Book-English-Final.pdf

Government of Karnataka & PwC. (2021). *Champion Services Sector Scheme: Transport & Logistics Sector*. https://vtpc.karnataka.gov.in/storage/pdf-files/CSSS%20Transport%20&%20Logistics.pdf

India Climate and Energy Dashboard. (2025). *State-wise Solar Potential* [Dataset]. https://iced.niti.gov.in/energy/fuel-sources/solar/potential

Karnataka Renewable Energy Development Ltd. (2022). *Karnataka Energy Conservation and Energy Efficiency Policy 2022-2027*. https://kredl.karnataka.gov.in/storage/pdf-files/EC/Energy%20Department%20(GoK)%20%20Notification%20on%20EE%20&%20EC%20Policy%202022-27.pdf

Kumar, R., Kumar, S., Yashavanth, B.S., Meena, P.C., Indoria, A.K., Kundu, S., Manjunath M. (2020). Adoption of Natural Farming and its Effect on Crop Yield and Farmers' Livelihood in India. ICAR-National Academy of Agricultural Research Management, Hyderabad, India. https://www.niti.gov.in/sites/default/files/2021-03/NaturalFarmingProjectReport-ICAR-NAARM.pdf

Kumar, S., Ansari, M.A., Choudhary, J., Ravisankar, N., Singh, R., Mehta, P. (2024). Organic Farming: Long-Term Influence on Soil Health and Produce Quality. Journal of the Indian Society of Soil Science, 72(Special Issue):134–144. https://doi.org/10.5958/0974-0228.2024.00064.3

Ministry of New & Renewable Energy. (2024, August). State-wise installed capacity of *Renewable Power*. https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2024/09/20240910506609784.pdf

Ministry of New and Renewable Energy. (2025). *Wind Overview*. https://mnre.gov.in/en/wind-overview/

Ministry of Road Transport & Highways,Government of India. (2025). *Vahan Dashboard* [Dataset]. https://vahan.parivahan.gov.in/vahan4dashboard/vahan/view/reportview.xhtml

MoEFCC. (2022). *India's Long-Term Low-Carbon Development Strategy*. https://unfccc.int/sites/default/files/resource/India_LTLEDS.pdf

NITI Aayog. (2024). *SDG India Index*. https://sdgindiaindex.niti.gov.in/#/ranking

Planning, Programme Monitoring and Statistics Department. (2023). *Karnataka Economic Survey 2022-23*. https://des.karnataka.gov.in/storage/pdf-files/Economic%20Survey%202022-23%20English.pdf

Planning, Programme Monitoring and Statistics Department. (2024). *Economic Survey of Karnataka 2023-24*. https://data.opencity.in/dataset/90aaf1df-999b-4d84-a0d0-443aee3d0bfc/resource/b96f076f-9b1c-48b2-bc1b-f081f1beca84/download/economic_survey_2023-24_finalenglish_compressed.pdf

10. Appendix

10.1. Stakeholder engagement

Figure A1 and Figure A2 provide a map of the different stakeholders we engaged with for the model development and validation within the government and the private sector, respectively.

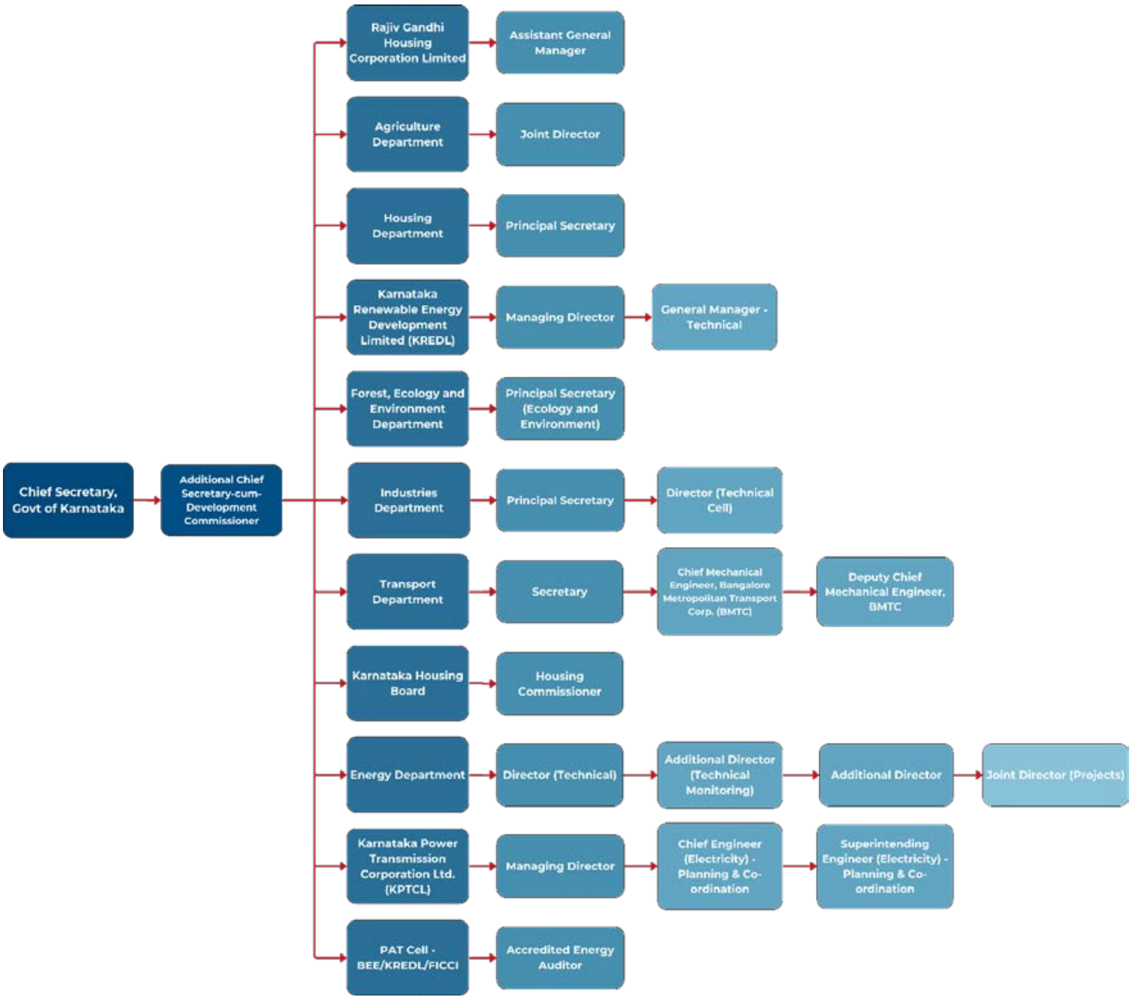


Figure A1: Stakeholder map for the Government of Karnataka

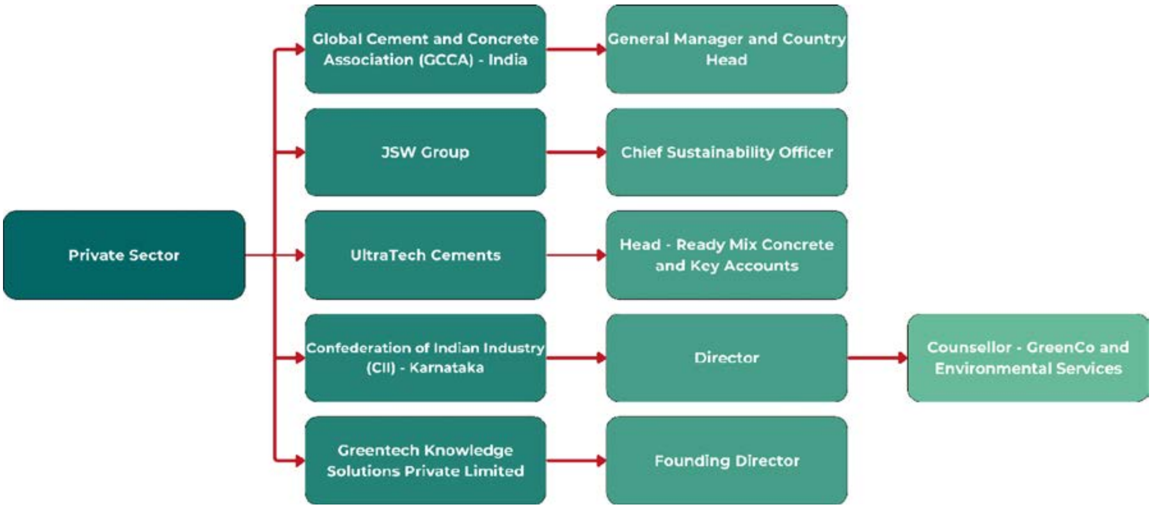


Figure A2: Stakeholder map for the private sector

10.2. Sectoral methodology and assumptions

This appendix provides an overview of the assumptions and methodology used to develop the *Namma* SAFARI model. We have made every effort to ensure that the data are accurate and reliable. Where data were unavailable, we relied on reasonable assumptions, validated as far as possible through expert reviews and stakeholder discussions. The model is designed to evolve, and we aim to keep refining it over time to ensure that it stays useful. We welcome feedback, queries, or suggestions, including improved data inputs, from all users and stakeholders.

10.2.1. Industry

The historical production for each industry was obtained from various data sources such as Perform, Achieve and Trade (PAT) Scheme from the Bureau of Energy Efficiency, the Indian Minerals Yearbooks (IMY) from the Indian Bureau of Mines, and the Annual Survey of Industries (ASI) from the Ministry of Statistics and Programme Implementation. A regression analysis was performed between historical production and historical gross value added (GVA) for the manufacturing sector to project annual growth rates and production numbers (in metric tonnes) for each industry until 2050. The modelling framework and methodology are shown in Figure A3 below.

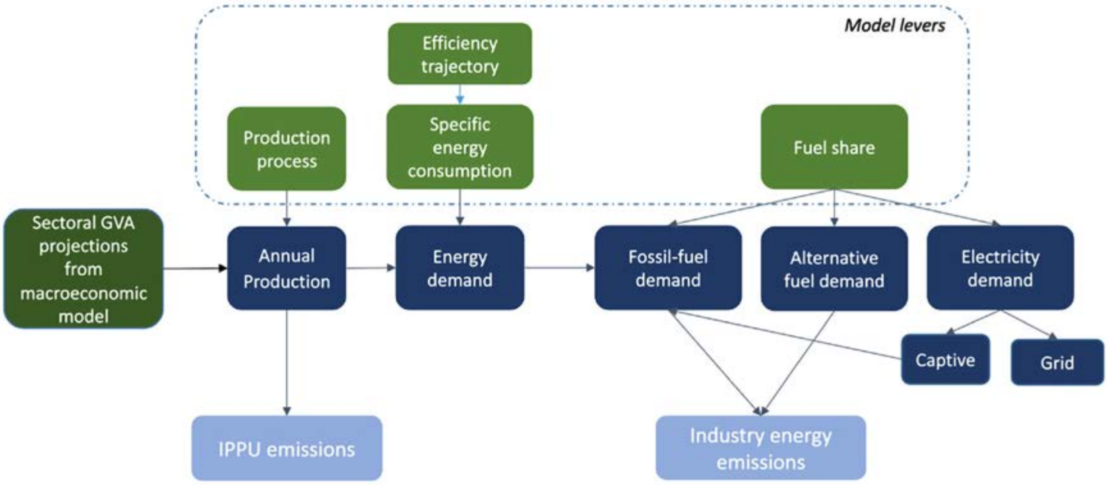


Figure A3: Modelling framework and methodology for the industry sector

The total energy demand was calculated using the production numbers and each industry's specific energy consumption (SEC) obtained from PAT notifications as well as annual reports from manufacturing companies in each respective sector. The formula for the total energy demand is as follows:

$$Total\ Energy\ Demand\ (TWh) = Specific\ Energy\ Consumption\ \left(\frac{TWh}{T}\right) * Total\ Production\ (T)$$

The total energy demand may be met by a variety of different fuel sources such as coal, petroleum coke, natural gas, furnace oil, electricity (captive and grid), and alternative fuels (e.g. biomass and waste). Each specific industry's fuel shares were obtained from company annual reports, Karnataka State Energy Calculator 2050, and Central Electricity Authority (CEA) reports. The total fuel demand was calculated for each type of fuel from the total energy demand, fuel shares and the respective net calorific value of each fuel, i.e. the total quantity of fuel required to generate 1 TWh of energy.

Finally, the total emissions were calculated by multiplying each fuel demand with the respective emission factor. The formula for fuel demand and emissions is given below:

$$Total\ Fuel\ Demand\ (MT) = Total\ Energy\ Demand\ (TWh) * Fuel\ Share * Net\ Calorific\ Value\ (\frac{MT}{TWh})$$

To create a low-carbon scenario, several levers were used such as production process share changes, fuel shares, material efficiency, and energy efficiency.

The investment needed for efficient production will include the additional marginal capital expenditure required by the industry to achieve this efficiency. Initially, the gap in efficient production is determined by assessing the efficient capacity currently available online and the maximum capacity utilisation factor (CUF) specific to the industry, as follows:

$$Gap\ in\ efficient\ production = \left(\frac{Efficient\ production}{Max\ CUF}\right) - Efficent\ Capacity\ available$$

The gap is the capacity that needs to be added annually to make the whole industry efficient. An annual cost is required to fill this gap and is calculated as follows:

$$\text{Annual cost for efficient production} = \text{Marginal extra capex} * \text{Annual efficient capacity addition}$$

The same methodology is followed for all industries considered for the study. The inputs taken for various quantities on which the scenarios are based are tabulated below

1. Steel Sector

    a. Steel production processes and their respective shares out of the total steel production

Year	Share of total steel production[1]				
	BF-BOF	COREX-BOF	DRI-EAF	H2 based DRI-EAF	IF
2015	42%	36%	16%	0%	6%
2025	35%	31%[2]	20.5%	0.5%[3]	13%

    b. Iron- and steel-making specific energy consumption (SEC)[4]

Iron-making process	BF	Smelting reduction	DRI Coal	DRI natural gas	DRI H2
SEC (GJ/Tonnes)	11.8	17	12.6	9.5	3.35

Steel-making process	BOF	EAF	Refining	Continuous casting
SEC (GJ/Tonnes)	1	5.6	0.4	0.1

1 Based on annual reports of all PAT-listed iron and steel industry units and Mineral Year Book (Indian Bureau of Mines)
2 Historical years assumed JSW BOF steel capacity to be equally linked to Blast-Furnace and COREX iron plants. Assumed phasing out of COREX plants in the future based on stakeholder consultation.
3 Assuming the JSW and KREDL green hydrogen plant gets commissioned by the end of 2025 (25 MW and 300 KW, respectively)
4 Based on a previous CSTEP study, validated by industry stakeholders

2. Cement Sector

a. Cement types and their historical shares (2015)[5]

Variety	Ordinary Portland Cement (OPC)	Portland Pozzolana Cement (PPC)	Portland Slag Cement (PSC)
Share	59%	38%	3%

b. Historical thermal and electrical SECs for cement manufacturing[6]

Year	2015	2016	2017	2018	2019	2020	2021
Thermal SEC (GJ/Tonnes)	2.525	2.583	2.560	2.555	2.577	2.556	2.565

Year	2015	2016	2017	2018	2019	2020	2021
Electrical SEC (kWh/Tonnes)	200	170	140	120.1	99.5	85	85

c. Historical fuel shares for cement manufacturing (2015–2025)

Fuel	Coal	Petcoke	Alternative fuel
Share	60% (57% in 2025)	40%	3% in 2025

3. Other Sectors: Specific Energy Consumption (SEC)

a. Aluminium

Year	2015	2020
SEC (TWh/Million tonnes)	8.61	8.34

b. Refinery[7]

Year	2015	2016	2017	2018	2019	2020	2021	2022
SEC (TWh/Million tonnes)	1.10	1.09	1.09	1.08	1.14	1.26	1.13	1.07

c. Fertiliser

Year	2015	2020
SEC (TWh/Million tonnes)	4.604	4.597

5 Based on annual reports of cement industries
6 Based on annual reports of cement industries
7 Based on the annual reports of Mangalore Refinery Private Ltd.

d. Textile

Year	2015	2020
SEC (TWh/Million tonnes)	9.05	8.68

e. Paper

Year	2020
SEC (TWh/Million Tonnes)	6.71

f. Other industries[8]

Year	2015	2021
SEC (TWh/INR billion)	0.13	0.09

4. Other Sectors: Fuel Shares[9]

a. Refinery

Fuel	Solid hydrocarbons	Liquid hydrocarbons	Gaseous hydrocarbons
Share	25%	40%	35%

b. Fertiliser

Fuel	Electricity	Natural gas	Furnace oil
Share	20%	79%	1%

c. Textile

Fuel	Coal	Petcoke	Diesel and furnace oil
Share	40%	45%	15%

d. Paper

Fuel	Coal	LPG
Share	99%	1%

8 All other industries: aggregate assumption on sectoral growth and SEC taken from the Karnataka State Energy Calculat
9 Based on annual reports of major industries and Karnataka State Energy Calculator

10.2.1.1. Validation

Figure A4 shows the actual[10] and simulated electricity demand from the industry sector from 2015 to 2024. The model simulation results lie within the range of the reported historic numbers according to the CEA report as well as the updated numbers in the CEA dashboard.

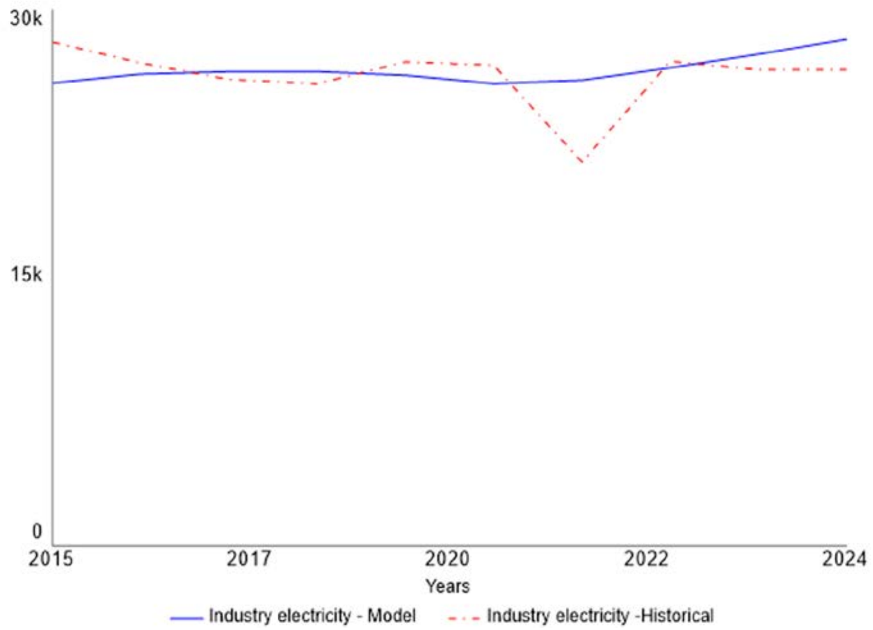


Figure A4: Comparison of historical electricity demand from CEA and simulated electricity demand from the Namma SAFARI model

10.2.2. Buildings

10.2.2.1. Commercial buildings

Commercial buildings in Karnataka are classified into two broad categories:

- **Service-driven buildings:** Includes offices, hospitality (hotels and restaurants), retail spaces, educational institutions, and healthcare facilities
- **Infrastructural buildings:** Includes airports, railway stations, K-RIDE stations, and metro stations—driven by rapid expansion in transport infrastructure

10.2.2.2. Methodology: Estimating built-up area

A **bottom-up, archetype-based approach** is used to estimate current and future built-up areas across sectors. Each typology is defined by its function and scale, using the following equation:

Built-up Area = Number of Units × Area per Unit

Variation in units by sector:

- **Hospitality**: Number of rooms **(FHRAI, India Tourism Statistics)**
- **Offices**: Number of employees **(Knight Frank)**
- **Retail**: Urban/Rural population × Retail space per capita **(JLL India)**
- **Education**: Number of schools/colleges **(Economic Survey of Karnataka)**
- **Healthcare**: Number of beds or centres **(CBHI, AHPI)**

10 Dashboard - Central Electricity Authority

- **Infrastructure**: Number of transport nodes (airports/stations)
- **Energy Performance Estimation**

10.2.2.3. Energy performance estimation

- **Index (EPI; kWh/m²/year)** values were taken from **BEE benchmarks**, sectoral reports, and case studies.
- For green buildings, **IGBC** and **LEED** case data informed improved EPI assumptions.
- Future energy demand is estimated by projecting built-up area growth using **sector-specific GDP regression models**.

10.2.2.4. Sector-wise built-up area assumptions

Assumptions:

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

10.2.2.5. Residential buildings

The historical electricity demand from the residential sector has been calibrated using data from CEA and Prayas datasets. Based on this, energy and emission projections for the sector have been developed through 2050, using 2015 as the base year. The overall modelling framework followed for developing the residential sector module is shown in Figure A5.

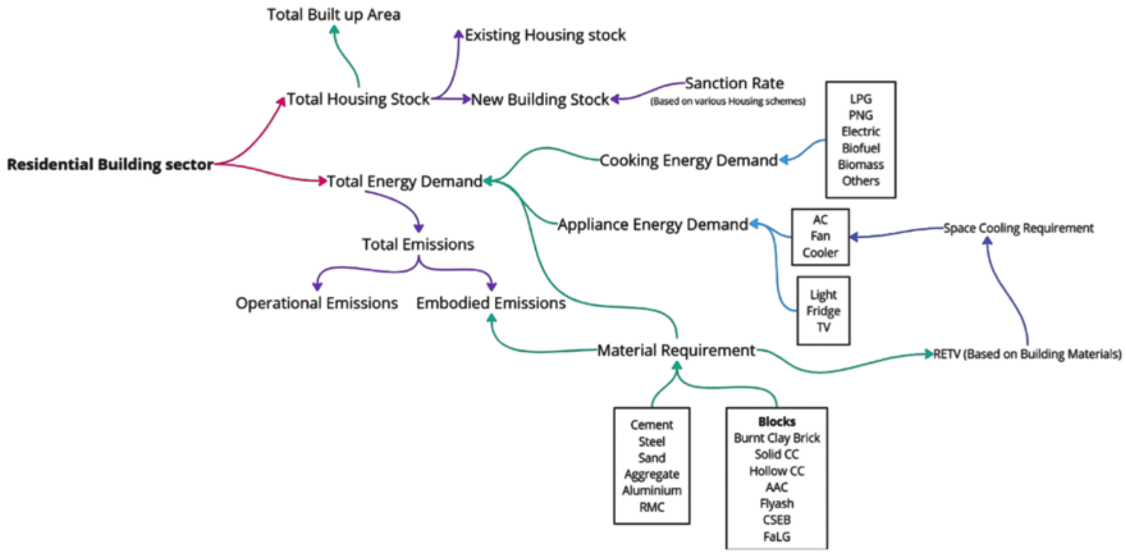


Figure A5: Modelling framework for the residential sector

Households: The population forecast in the model is based on the population growth rate, which is calculated based on the population projections based on the Census of India 2011[11]. Based on the delineation of geographical area, the population in Karnataka is divided into urban and rural. The average household size is taken as 3 for urban and 4.2 for rural, assumed to follow a decreasing trend for rural, which in turn gives the urban and rural household numbers. The urban population is further subdivided based on income category into Economically Weaker Section (EWS) / Low-Income Group (LIG) and Middle-Income Group (MIG) / High-Income Group (HIG). The share of EWS/LIG households is taken as 65% in 2015 and assumed to follow a decreasing trend as it reaches 58% by 2050[12].

Housing Shortage: The total housing stock in Karnataka is modelled considering the existing housing stock in 2015 (based on Census 2011) and the annual addition of houses each year. Existing houses pass through an ageing chain and become obsolete after 40 years. New constructions in EWS/LIG and rural areas are based on the sanction rates for various central housing schemes (such as PMAY) and state housing schemes (e.g. Devaraj Housing scheme, Vajpayee Housing schemes, and Dr B R Ambedkar Housing Schemes)[13]. For the MIG/HIG category, voluntary construction of houses is considered, assuming the housing requirement is fully met. The housing shortage is estimated as the difference between the total number of houses required based on population and the total number of available houses in each category for every year.

Material Requirement: The built-up area of each EWS/LIG house is taken as 45 sq m and is expected to reach 60 sq m by 2030. For MIG/HIG, the area increases from 100 sq m in 2020 and reaches 150 sq m in 2050, and for rural areas, it is taken as 60 sq m. With the addition of 10% common space area, the total built-up area in each category is obtained by multiplying it with the total number of households in each category. Considering load-bearing structures for conventional buildings, the share of different building blocks is considered, which includes Burnt Clay Brick, AAC blocks, Hollow CC blocks, FaLG blocks, Solid CC blocks, SEB blocks, and Flyash blocks. The requirement of construction materials such as cement, steel, sand, and aggregate for the new construction is also estimated based on the additional built-up area each year.

11 Report of Technical Group on Population Projections, published in July 2020,
12 Affordable Housing Policy 2016
13 Economic Survey of Karnataka 2023-24

With respect to the material estimate, the total embodied energy and the related embodied emissions from Karnataka's housing sector are calculated for the future years[14]. Moreover, rapid construction technologies, including Mivan shuttering, are modelled to capture the construction trends, with additional materials such as RMC and aluminium.

Thermal Comfort: Cooling demand for urban and rural households is calculated by combining the sensible heat gain (due to temperature differences across building envelopes and roofs) and latent heat gain (due to humidity). The total cooling load is estimated with indoor temperatures of 26°C.[15]

Sensible Heat – Building Envelope: Sensible cooling demand through walls and windows is calculated using the **Residential Envelope Transmittance Value (RETV)** formula adopted from the Energy Conservation Building Code for Residential Buildings[16]. RETV values are estimated for each construction material and alternative building technology, weighted by material shares in the building stock. The final RETV values are converted into cooling loads using a linear regression model derived from energy simulations. Orientation and window-to-wall ratio (WWR) values are assigned based on the two main climate zones considered—**warm and humid** (50%) and **hot-dry/ composite** (50%).

Sensible Heat – Roofs: Cooling demand from roofs is estimated using the thermal transmittance **(U-value)** of roofing materials, calculated using the methodology prescribed in ENS 2018. A weighted average U-value is derived based on the roof material mix obtained from Census 2011 and the National Buildings Organisation data. The adoption of cool roofs is modelled with an added layer of cool roof materials, such as tiled, coated, membrane, and green roofs, considering the existing cool roof policies in the country[17].

Latent Heat Gain: Latent heat load is calculated using simulation results across different climatic zones. The latent cooling demand per unit built-up area is assumed to be constant across rural and urban households for the modelling period[18].

Appliances and Cooking: Based on the household number and appliance penetration from the PIER database[19], the total appliance stock is calculated. The appliances considered include air-conditioner (AC), fan, cooler, lighting, fridge, and television. The power, hours of use, and efficiency of each appliance are used to calculate the operational energy of appliances. The RETV value of a building under different material shares is calculated, and the total cooling load is estimated considering 26°C as the set point temperature. The number of ACs in a household is made dynamic to meet this cooling load, thus connecting the building envelope and AC energy demand. The total cooking energy is calculated based on household numbers in each category. The annual average cooking energy is taken as 708 kWh/year, and the cooking energy is estimated based on the share of cooking fuel (LPG, PNG, electricity, biomass, biogas, and others)[20]. The energy used for both appliances and cooking is combined to give the total operational energy of the buildings annually. Thus, the operational and embodied energy is further added to give the total energy demand from the buildings sector in Karnataka. The total greenhouse gas (GHG) emissions from the buildings sector are similarly calculated to analyse the GHG implication of achieving the goal of safe and affordable housing for all in Karnataka.

Rooftop Photovoltaics: Solar energy generation from rooftop PV systems is estimated for **residential and commercial buildings** in both urban and rural areas. The total RTPV generation depends on roof availability, solar radiation, RTPV adoption rate, and technology efficiency. The available roof area for RTPV across rural and urban contexts is estimated using a rooftop to BUA ratio (0.24 for urban and commercial and 0.7 for rural) based on model analysis.

14 Pathways to steer India's buildings sector towards a net-zero future, CSTEP, 2024

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

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

17 Government of Telangana. (2023). Telangana Cool Roof Policy 2023—2028.

18 Pathways to steer India's buildings sector towards a net-zero future, CSTEP, 2024

19 https://energy.prayaspune.org/our-work/data-model-and-tool/rumi-pier

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

The following formula is used to estimate RTPV energy:

Energy from RTPV = Usable roof area × RTPV adoption rate × Solar radiation × Conversion efficiency

The **usable surface area** is assumed to be **20% of the total roof area**, based on expert consultations. Solar radiation is taken as **1770 kWh/m²/year.**[21] **RTPV conversion efficiency** is assumed at **20%**, reflecting recent improvements in PV technology as per the national SAFARI model[22].

The RTPV adoption rate is calculated using electricity demand data and the **installed capacity projections** from the National Renewable Energy Laboratory (NREL). These projections estimate rooftop capacity to reach **50 GW by 2050,** assuming that the RTPV adoption rate reaches almost 50%. Historical data on installed RTPV capacity from **MNRE Annual Reports (2015–2022)** are used for calibration[23].

10.2.2.6.Validation

Figure A6 shows the actual[24] and simulated electricity demand from commercial and residential sectors from 2015 to 2024. The model simulation results lie within the range of the reported historic numbers according to the CEA report as well as the updated numbers in the CEA dashboard.

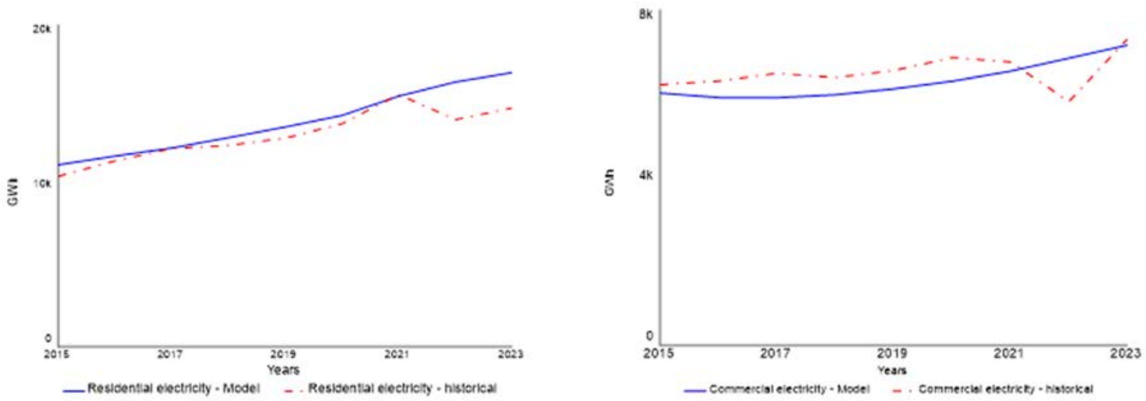


Figure A6: Comparison of historical electricity demand from CEA and simulated electricity demand from the Namma SAFARI model

10.2.3. Transport

The transport sector in Karnataka is broadly divided into passenger and freight transport, which are further categorised by mode (road, rail, air, and waterways) and by vehicle type (such as two-wheelers, three-wheelers, light passenger vehicles, buses, and light/medium/heavy commercial vehicles). Within each mode and vehicle category, transport is further disaggregated by fuel type, including petrol, diesel, electricity, CNG, LPG, aviation fuel, and bunker fuel. The model estimates transport demand across each mode, vehicle category, and fuel type. Based on these estimates, it calculates the corresponding fuel consumption and emissions. A brief overview of the methodology and key assumptions are provided below.

21 Solar Grid - Karnataka Renewable Energy Development Limited
22 Pathways to steer India's buildings sector towards a net-zero future, CSTEP, 2024
23 Cumulative Installed Capacity (Financial Year-wise) | MINISTRY OF NEW AND RENEWABLE ENERGY | India (mnre.gov.in)
24 Dashboard - Central Electricity Authority

10.2.3.1. Passenger transport

Passenger transport in Karnataka operates through four main modes (road, rail, air, and waterways) and includes both intercity and intracity movement. Intracity transport is primarily road-based, including three-wheelers, buses and private vehicles, along with suburban rail or metro systems in urban areas. Intercity transport, on the other hand, spans all four modes of travel, with varying shares.

The modelling approach for passenger transport is driven by passenger-kilometres travelled (pkm). The per capita pkm is estimated using a GDP-driven growth rate[25], reaching a saturation level of 18,000 pkm per capita[26]. This value is then multiplied by the total population of Karnataka[27] to calculate the total pkm (Figure A7) for Karnataka, as shown in the equation below.

$$Total\ pkm\ =\ per\ capita\ pkm \times total\ population$$

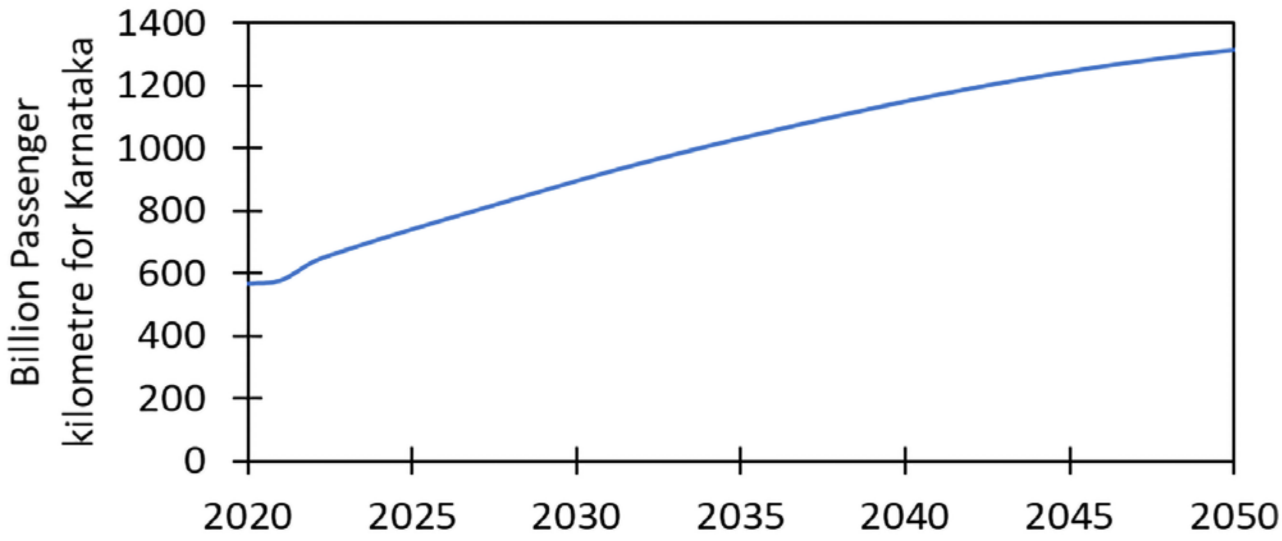


Figure A7: Estimated passenger-kilometres travelled (billion pkm) for Karnataka

The total pkm is first divided into intracity and intercity travel and then allocated across different modes, i.e. road, rail, air, and waterways, based on their respective mode shares.

Intracity Passenger Transport: For modelling intracity passenger transport, cities are divided into two categories: those with a population of more than 5 million (primarily Bengaluru) and those with a population of less than 5 million (rest of the urban cities). The urban households of Karnataka are classified into LIG and MIG/HIG to account for differences in yearly trip rates. The growth of shares of LIG and MIG/HIG households in the total urban households in Bengaluru and other cities are estimated from the literature[28]. One of the major steps in developing a travel demand model is the generation of trip rates, which is largely impacted by the population, household income, average vehicle ownership, household structure, and family size. In a general form of trip generation, the number of trips is expressed as a linear combination of the aforementioned variables[29]. In this study, household structure is considered a key variable influencing the number of trips. It is represented by the number of bedrooms in a dwelling. For analysis, 1 and 2 BHK units are classified under LIG, whereas 2 and 3 BHK and larger units are categorised under MIG/HIG. A linear relationship between the number of trips and household structure is modelled using historical data[30]. The equation below shows the linear relation between the two variables.

$$y = 1.3 \times x - 0.33$$

25 Adopted from Karnataka Energy Calculator GDP growth rate
26 https://cstep.in/drupal/sites/default/files/2020-06/CSTEP_RR_SAFARI_2020.pdf
27 Karnataka (India): Districts, Cities and Towns - Population Statistics, Charts and Map". www.citypopulation.de. Retrieved 19 April 2019.
28 https://www.civil.iitb.ac.in/~vmtom/nptel/203_InTse/web/web.html
29 https://www.civil.iitb.ac.in/~vmtom/nptel/203_InTse/web/web.html
30 https://tripgen.excelinnova.net.in/household/results/all

where is the number of trips and is the number of bedrooms in the house. The average trip lengths for Bengaluru and other cities are collected from the literature[31]. Relevant information for intracity pkm, including the number of trips per person per day, and the average trip length are then assigned to each category, reflecting different travel patterns and needs.

These households are distributed among the two city types according to population ratio. Intracity pkm is calculated using trip rates, average trip length, and population, as shown below:

$$Annual\ intracity\ pkm = \frac{No.\ of\ trips}{days} \times \frac{Length\ of\ trip}{Trip} \times Population \times 365$$

The annual intracity pkm is then distributed across different transport modes—two-wheelers, three-wheelers, passenger cars, and buses—based on their respective modal shares. Each mode-wise pkm is further disaggregated by fuel type according to its corresponding fuel share. Table A1 shows assumptions on modal and fuel shares for passenger transport in 2020 and 2050. Using the mode-wise pkm and fuel share information, the fuel demand is estimated as follows:

$$Fuel\ demand_i = Mode - wise\ pkm \times fuel\ share_i \times fuel\ economy$$

where *i* represents various fuel types such as petrol, diesel, electricity, CNG, and LPG. The fuel economy for different vehicle modes is expressed in litres/pkm and sourced from various references as detailed in the supplementary sheet.

31 https://dult.karnataka.gov.in/assets/front/pdf/Comprehensive_Mobility_Plan.pdf

Table A1: BAU assumption on modal and fuel shares across intracity passenger transport

Intracity passenger transport					
Vehicle category	Modal share		Fuel type	Fuel share	
	2020	2050		2020	2050
Two-wheeler	30%	22%	Petrol	100%	68%
			Electricity	0	32%
Three-wheeler	10%	10%	LPG	1.03%	5%
			Diesel	86.5%	10%
			Electricity	0.5%	40%
			CNG	11.9%	45%
Cars	15%	35%	Petrol	68%	67%
			Diesel	35.8%	23%
			Electricity	0.16%	10%
Cabs	1%	1%	Petrol	15%	0%
			Diesel	71.9%	60%
			Electricity	0.13%	20%
			CNG	13%	20%
Buses	15%	10%	Diesel	100%	92%
			Electricity	0	3.93%
			CNG	0	4.09%
Metro	10%	17.5%	Electricity	100%	100%
Non-motorised transport	19%	7.5%			
Intercity passenger transport					
Buses	90%	78.9%	Diesel	100%	86.3%
			Electricity	0	10%
			CNG	0	4.09%
Rail	10%	21.1%	Diesel	77%	0%
			Electricity	23%	100%
Aviation	3.65%	3.74%	Aviation fuel	100%	97.5%
			Biofuel	0%	2.5%

Sources: The modal share for Bengaluru and other cities is obtained from multiple sources[32,33,34,35]. Historical fuel share numbers are derived from the Vahan database. A similar fuel share trend is assumed to be followed for the reference scenario.

32 https://www.researchgate.net/publication/317227046_Equity_in_public_transport_-_a_case_of_Bangalore's_city_bus_transport
33 https://dult.karnataka.gov.in/assets/front/pdf/Comprehensive_Mobility_Plan.pdf
34 https://transformative-mobility.org/wp-content/uploads/2023/12/Bangalore-Deep-Dive.pdf
35 https://dult.karnataka.gov.in/assets/front/pdf/Comprehensive_Mobility_Plan.pdf

Intercity Passenger Transport: The intercity pkm is calculated by subtracting intracity pkm from the total pkm. Intercity travel predominantly comprises buses and taxis, which are further categorised by fuel types (i.e. petrol, diesel, CNG, and electric). Fuel demand for intercity passenger transport is then calculated following the same methodology as previously described.

10.2.3.2. Freight transport

Freight transport is modelled in a similar way as passenger transport, starting with the estimation of tonne-kilometres (tkm) per capita, driven by GDP growth and reaching a saturation value of 11,000 tkm per capita[36]. This value is then multiplied by the total population of Karnataka to determine the total tkm (Figure A8) for freight movement, as shown below.

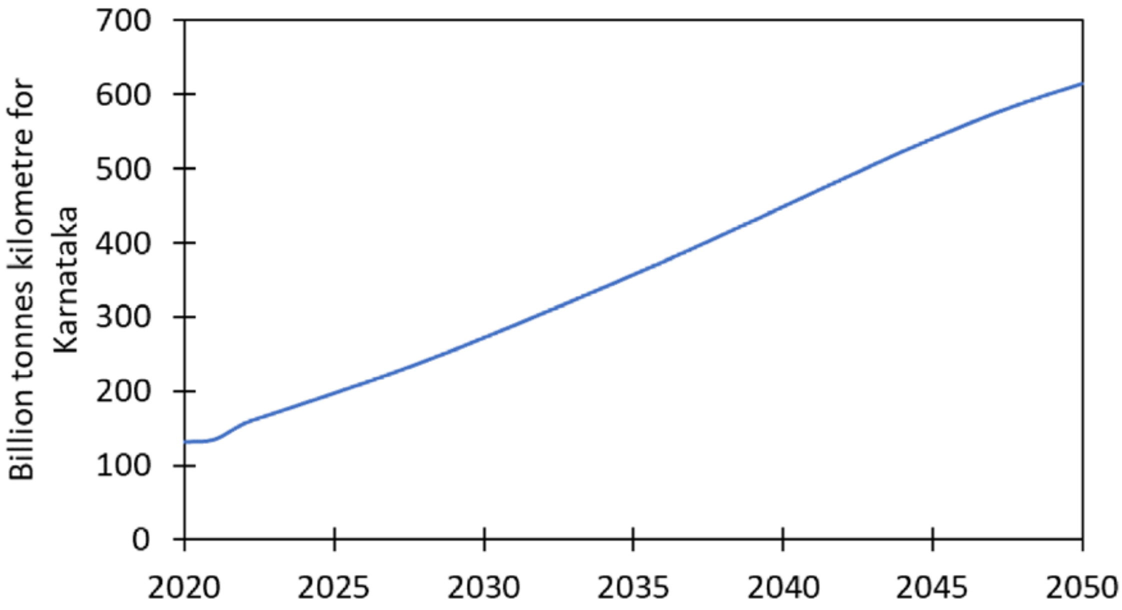


Figure A8: Estimated tonnes-kilometre (billion tkm) for Karnataka

The total tkm is then allocated across different transport modes (road, rail, air, and waterways) to obtain mode-wise tkm. The mode-specific tkm is further divided by fuel type, based on the fuel share for each mode. Table A2 shows the assumptions for modal and fuel shares for freight transport in 2020 and 2050. For road freight, two vehicle categories are considered: light commercial vehicles (LCVs) and medium and heavy commercial vehicles (MCVs + HCVs). Using mode-wise tkm and fuel share information, the fuel demand is estimated as follows:

$$Fuel\ demand_j\ =\ Mode - wise\ tkm \times fuel\ share_j \times fuel\ economy$$

where represents various fuel types such as petrol, diesel, electricity, hydrogen, LPG, ATF, and bunker fuel.

Total GHG emissions are estimated by applying specific emission factors for CO_2, N_2O, and CH_4 to the estimated fuel consumption data. These emission factors quantify the amount of each gas emitted per unit of fuel burned, allowing for the calculation of overall emissions across all transport modes and fuel types.

36 https://cstep.in/drupal/sites/default/files/2020-06/CSTEP_RR_SAFARI_2020.pdf

Table A2: Assumption on modal and fuel shares across freight transport

Mode of transport	Modal share		Fuel type	Fuel share	
	2020	2050		2020	2050
LCV	8.85%	8.1%	Diesel	86.8%	60%
			Electricity	0.353%	10%
			CNG	13%	30%
HCV	78.75%	54%	Diesel	90%	78%
			CNG	10%	22%
Rail	12.4%	37.9%	Diesel	77%	0%
			Electricity	23%	100%

Source: Modal shares are derived from the Karnataka State Energy Calculator. Fuel shares for road-based freight are obtained from the Vahan database and assumed to follow a similar trend in the future. Data related to rail-based freight are taken from the literature[37][38].

10.2.3.3. Vehicle stock model

To estimate the operational vehicle stock, a stock-and-flow model was developed, compensating for the lack of data on retired vehicles in the Vahan database. This model uses the annual registration data from Vahan across various vehicle categories, including two-wheelers, three-wheelers, four-wheelers, buses, LCVs, and MCVs + HCVs, from 2001 to 2024. The new vehicle registrations in each year serve as inflows, while the estimated service life for each vehicle category informs the outflows, which help calculate the operational stock over time. For two-wheelers and three-wheelers, a service life of 10 years was assumed, after which all vehicles in these categories are considered retired. For four-wheelers, a phased-ageing chain approach was used: 10% retire after 10 years, 90% move into the second phase at 10–20 years (with 40% retiring during this period), and the remaining transition to a final stage (20–30 years), retiring fully after 30 years. Similarly, for buses, LCVs, MCVs, and HCVs, 20% of vehicles retire after 10 years, with the remaining 80% moving into the second stage at 10–20 years, retiring at 20 years. The model uses these inflows and structured outflows to calculate the operational stock of each vehicle category annually, generating a realistic estimate of vehicles still in service.

37 https://indianrailways.gov.in/railwayboard/uploads/directorate/ele_engg/2023/Railway%20Electrification%20as%20on%2001_04_23.pdf

38 https://indianrailways.gov.in/railwayboard/uploads/directorate/ele_engg/pdf/RE%20Upload.pdf

10.2.3.4. Model validation

Figure A9 compares the actual (from MoPNG[39]) and simulated petrol and diesel demand from 2015 to 2024.

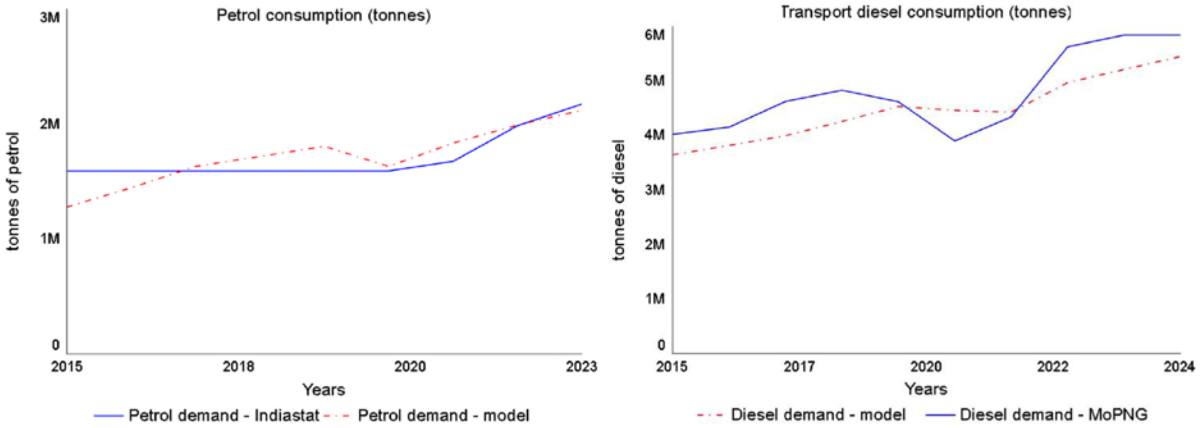


Figure A9: Comparison of historical diesel demand from MoPNG and simulated diesel demand from the Namma SAFARI model

10.2.4. Agriculture pumping energy

The energy (electricity, solar, and diesel) and associated emissions required to pump the volume of groundwater for irrigation are estimated based on water-level depth, average pump power, and the number of pumps. The total number of pumps is divided into diesel, solar, and electric pumps.

The number of electric pumps is determined by multiplying the percentage of electrified pumps in Karnataka by the total number of pumps:

Number of electric pumps = (% pump electrification) × (total number of pumps)

Similarly, the number of solar pumps is calculated using the percentage of solarised pumps in the current year and projected values for 2050 and 2100. After electrification and solarisation, the remaining pumps are assumed to be diesel-powered.

Electricity demand for groundwater pumping is calculated based on the number of electric pumps, the power consumption of each electric pump, the average annual operating hours per pump, and a motor efficiency factor.

$$\begin{aligned} &Electricity\ consumption\ for\ groundwater\ pumping \\ &\qquad = \left(\frac{power\ consumption\ by\ one\ electric\ pump}{(motor\ efficiency)}\right) \\ &\qquad * (Number\ of\ electric\ pumps \\ &\qquad * Average\ number\ of\ working\ hours\ per\ year\ per\ pump) \end{aligned}$$

39 PETROLEUM STATISTICS - Indian PNG Statistics | Ministry of Petroleum and Natural Gas | Government of India

The diesel requirement for groundwater pumping is calculated using the following formula:

$$\begin{aligned} &\textit{Tonnes of oil equivalent for groundwater pumping} \\ &\quad = \textit{Number of Diesel pumps} * \textit{Diesel consumption by one pump} \\ &\quad * \textit{Tonnes of oil equivalent per litre of diesel} \\ &\quad * \textit{Average number of working hours of pump per year} \end{aligned}$$

We considered the decentralised solar capacity and capacity under PM-KUSUM that will supply electricity to IP sets and agri-feeders.

10.2.4.1. Validation

Figure A10 compares the actual (from CEA[40]) and simulated petrol and diesel demand from 2015 to 2024.

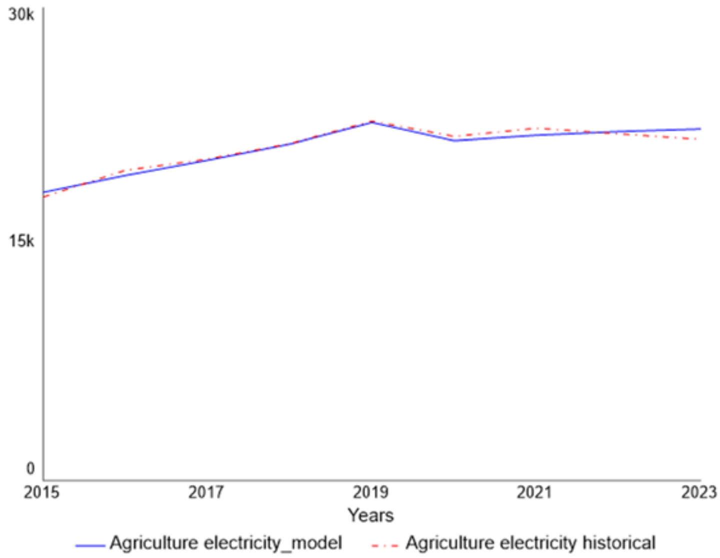


Figure A10: Comparison of historical electricity consumption from CEA and simulated electricity demand from the Namma SAFARI model

10.2.5. Land-use and forestry sector

Land use is the surface utilisation of all developed and vacant land on a specific point at a given time and space. Some land is more suitable than others for a specific use, such as agricultural land is present in areas with high soil fertility, access to water, and other topographic specifications that are necessary for cultivation. On the other hand, buildings and industries are built on land that can support heavy construction and are close to transportation facilities and transmission lines. However, these areas can be overlapping, and the changes in land from one land-use type to another are termed land-use change. Land use and land cover (LULC) changes have previously led to land degradation, reducing carbon sequestration potential and soil fertility. Thus, optimised land-use management and land allocation are necessary to achieve both developmental goals and climate targets.

10.2.5.1. Data and model

Karnataka is divided into 30 administrative districts, further subdivided into 178 sub-districts (taluks) for decentralised governance, covering more than 27,481 villages and 367 towns with a population of 64.06 million (density: 320 people per km^2). According to the LULC maps provided by the National Remote Sensing Centre (NRSC), the state has 18 land classes. For this study, we aggregated these land classes to reflect six main land classes of the state: Agriculture land (net sown cropland and fallow land), Forestland, Wasteland, Grassland, and Built-up land. Of these classes, 60% land on average is occupied by agriculture land, followed by forestland occupying about 28% land on average. The rest of the land is occupied by wasteland (6%), built-up land (3%), and other

40 Dashboard - Central Electricity Authority

land categories (3%), which include water bodies and some alpine and sub-tropical grasslands. We performed a trend analysis on these classes to understand the historical changes each of these land classes has undergone. Most land categories, as per the NRSC dataset, have remained relatively constant over the years (2005–2021). However, a few trends can be observed. In the agriculture land class, net sown cropland has grown from 2005 to 2021 by 20%, while fallow land has decreased by 40% during the same period. Forestland has remained almost constant, with only a 0.1% increase observed from 2005 to 2021. Wasteland, on the other hand, has decreased by 16% in the past two decades, and built-up land has increased by 13%. These trends point towards an ongoing land-use interaction, and this is outlined in the correlation matrix given in Figure A11.

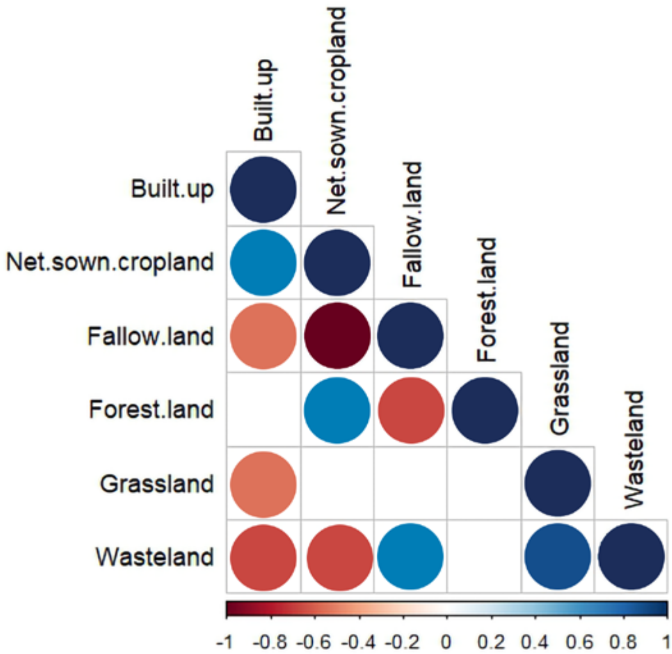


Figure A11: Correlation matrix of aggregated land categories for Karnataka

We observed a strong correlation between net sown cropland and fallow land ($r = -0.99$, $p<0.001$), indicating a strong interaction between the two land classes. Similarly, built-up land and wasteland also show a strong negative correlation ($r = -0.69$, $p<0.01$). Fallow land and built-up land also show an interaction ($r = -0.5$, $p<0.05$). This interaction is also corroborated by the trend analysis, with the decrease in fallow land being more than the increase in net cropland, which indicated fallow land interaction with other land categories as well. An interaction that was not observed in this analysis but can be found in literature and through expert consultations is the interaction between forestland and wasteland. Forest land expansion usually occurs on wasteland, which are targeted sites for afforestation drives across the nation. This was not observed in our analysis because of the limited timeframe and the limited expansion of forest in the given time frame. Based on these analyses and stakeholder consultations, we developed the land sector model. However, the forest sector model was developed in detail as a separate exercise and then interlinked with the land sector model based on the interactions described in this section.

The state's forest ecosystem is both unique and highly diverse, shaped by the interaction of topography, climate, and soil conditions, as well as altitude and proximity to the sea. The forest types range from tropical evergreen and semi-evergreen to moist and dry deciduous, thorny scrubs, sholas, and coastal mangroves. We used the data provided in the India State of Forest Reports (ISFR) provided by the Forest Survey of India (FSI). These reports are generated biennially, and we used ISFR 2013 to ISFR 2021 to obtain forest and tree cover data from 2011 to 2019.

Historical data for area under forest cover is provided in the ISFR, which also classifies the area into three classes based on density: very dense forests (VDF), moderately dense forests (MDF) and open forests (OF). ISFRs further provide data on scrub/degraded forests as well. The definition for each class is provided in Table A3. Additionally, ISFR also provides data on the change in forest cover under each class and the changes between forests and non-forest class. These data are used for forest cover calculations in the model.

The area under tree cover is given separately by the ISFR reports, and this is considered without modifications in the model. It is assumed that no deforestation or degradation occurs in the area classified as tree cover. The historical trend in the increase in tree cover is considered the area afforested in the land classified as tree cover.

Table A3: Forest cover classification in terms of canopy density

Class	Description
Very dense forest	All land with a tree canopy density of 70% and above
Moderately dense forest	All land with a tree canopy density of 40% and above but less than 70%
Open forest	All land with a tree canopy density of 10% and above but less than 40%
Scrub	Forest land with a canopy density of less than 10%

10.2.5.2. Land-use model

Figure A12 describes the basic model structure for land use. In the land-use sector, the model is based on trend analysis, correlation analysis, and expert consultations, described previously. In the structure, all land categories are represented as 'stocks' (rectangular boxes) that interact with each other via 'flows' (blue arrows). The rate of flow between each stock is dependent on the sectoral demand from every sector. The number on the flow represents the priority assigned to that category for conversion. The details of the structure are given below.

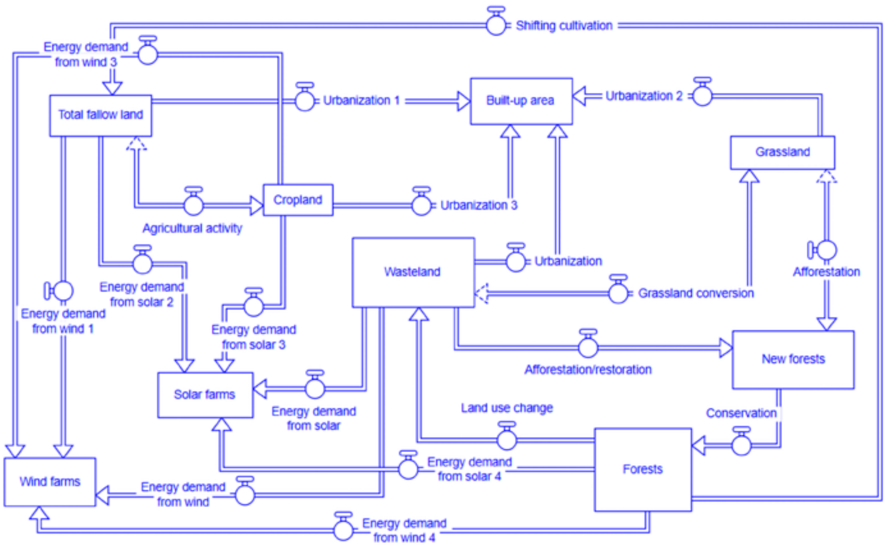


Figure A12: Basic model structure for Karnataka land-use sector

Agricultural activity: This flow describes the relationship between the total fallow land and cropland classes. In the model, the area under cropland is further divided into food crops and other crops. This disaggregation is done based on the data given in the land use statistics report (Ministry of Agriculture and Ministry of Statistics). Food crops include all cereals and pulses, while other crops include cash crops such as sugarcane, oil seeds, fruits, and vegetables. Land-use statistics report provides the gross cropland under each of the crops, which includes the area cultivated more than once in a given year. To convert this into the net sown cropland, we use cropping intensity (gross land/net sown land). The historical growth in these crops drives the demand for land under net sown cropland, which in turn drives the agricultural activity flow.

Energy demand for wind and solar: There are multiple flows for the land demand arising from the energy demand from wind and solar generation. This demand, calculated in the power sector, is converted into the land demand based on the land footprint of wind and solar farms. Land footprint describes the area required for the generation of 1 GW energy (Ha/GW). An average land footprint of 25,000 Ha/GW (19,000–35,000 Ha/GW) for wind power and 3000 Ha/GW (1200–4800 Ha/GW) for solar power is used in the model (von Krauland, 2024).

However, not all land has the potential to generate either wind power or solar power or both. We conducted a literature review to identify land classes and estimate the area within these classes with power generation potential. Kiesecker et al. (2020) estimated the maximum land that will be affected based on the potential of wind and solar power generation in each land class, as per NRSC data (aggregated land classes were also used in their study). These values were used as a threshold for land conversion, after which the next land priority is considered for conversion. The priority used in the model is wasteland > fallow land > (net sown cropland = forestland = grassland) (Kiesecker et al., 2020). The overlap in land for both solar and wind is also considered in the model to avoid counting duplication.

Urbanisation: These flows in the model describe the interaction between built-up land and other land categories that provide land for the expansion of built-up land. A priority is assigned for the conversion of different land classes to built-up land class (wasteland > fallow land > grassland > net sown cropland). Forest land interaction with built-up land occurs via wasteland conversion (land-use change flow; see forest land model for details).

10.2.5.3. Forest model

Figure A13 represents the basic structure of the forest model for Karnataka. As mentioned previously, each flow is based on the change matrix data provided in the ISFRs.

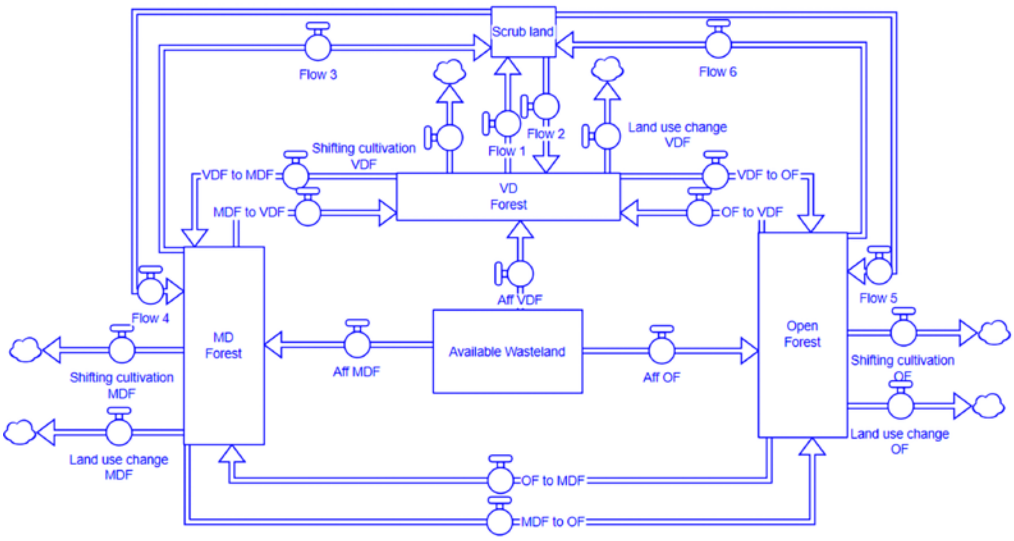


Figure A13: Basic model structure for Karnataka land-use sector

Afforested forests: Any non-forest land that is converted to forest land is considered an afforested area. Afforested areas are considered young forests until 20 years, beyond which they are considered old-growth forests. This creates two age classes—less than 20 years and greater than 20 years. This is represented by Aff VDF, Aff MDF, and Aff OF flows in the model structure.

Degraded and restored areas: The transition from forest land to scrubland (flows 1, 3, and 6) or from high-density forest to low-density forest classes—conversion of VDF to either MDF (VDF to MDF flow) or OF (VDF to OF flow) or conversion of MDF to OF (MDF to OF flow)—is considered degradation. Conversely, the conversion of scrubland to forest land (flows 2, 4, and 5) or the conversion of low-density forest land to high-density forest land (MDF to VDF flow, OF to VDF flow, and OF to MDF flow) is assumed to be a result of restoration activities, and thus, the converted area is considered restored area.

Deforested areas: Two main causes of deforestation are considered in this model)—shifting cultivation and land-use change. The conversion of any forest land to non-forest land in the change matrix is considered deforested area. This is then apportioned into the two types of flows (shifting cultivation VDF, MDF, and OF and land-use change VDF, MDF, and OF) based on the reasons provided in the ISFR.

As mentioned previously, this was not performed for tree cover data, which is assumed to grow at the historical average rate as per ISFR data.

In the forest model, we also calculate the total carbon sink and the annual carbon capture based on photosynthetic productivity (net primary productivity [NPP]), the volume of wood per hectare, and the average wood density of the tree species in the forests and tree cover. Average canopy density is used as a weightage to differentiate between the carbon capture ability of each density class.

10.2.5.4. Validation

Figure A14 Shows the simulated model runs comparison with actual data from NRSC[41], LUS[42]and FSI[43], and shows close alignment.

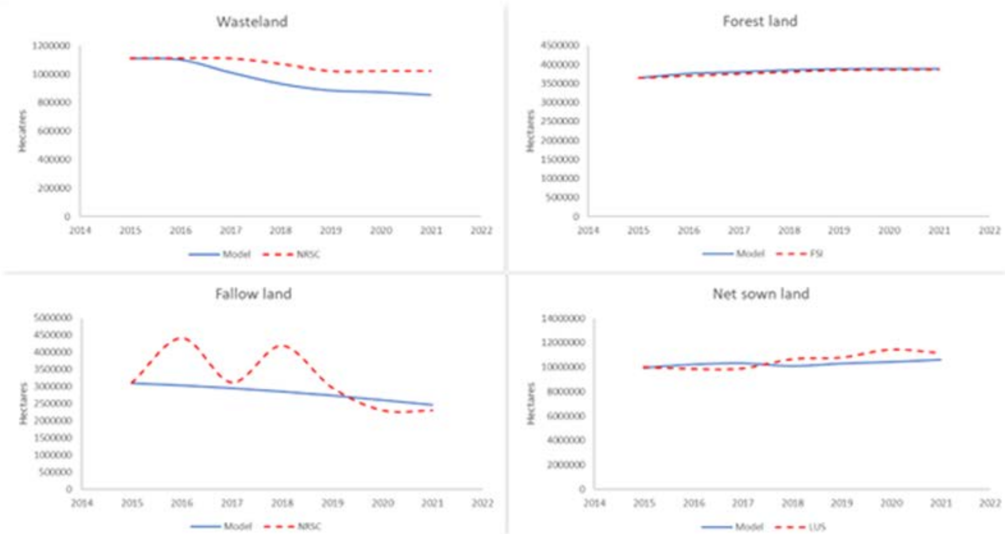


Figure A14: Comparison of historical data of land-use change of different classifications vs. modelled land-use change

10.2.6. Power

The electricity supply module of SAFARI is built to respond to demand and meet the overall demand for all scenarios. It captures interactions between electricity demand, electricity supply, and other resources. Supply sources being considered include coal, central generating stations, independent power producers (IPPs), large hydro, solar PV, wind, biomass, micro-hydro, and grid storage like pumped hydro and battery. The model considers Karnataka as one spatial unit and runs at an annual time step, although it accounts for demand–supply variations at different time scales, like diurnal and seasonal.

The demand drivers in the SAFARI model are the selected development goals (food, housing, healthcare, education, transport, clean cooking, water, and power) and socio-economic parameters (such as population and GDP). GDP is an output from our macroeconomic computable general equilibrium (CGE) model (CSTEP, 2020a), soft-linked to SAFARI. The CGE model is driven by investments.

41 https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php
42 https://desagri.gov.in/document-report-category/land-use-statistics-at-a-glance/
43 Welcome To Forest Survey of India

The total energy demand estimated (from development goal needs and demand for materials) comprises electric and thermal energy. The electricity demand is then used as an input for the power sector part of the SAFARI model to estimate future growth in installed capacity and generation. The model includes fossil-fuel sources, such as coal, and fossil fuel-free sources, such as hydro, nuclear, biomass, solar, wind, and firmed-up renewable energy (RE). Possible capacity addition in the power sector is also limited by the availability of water, land, and resource potential (wind and solar).An important output of the SAFARI power model is GHG emissions from electricity generation.

10.2.6.1. Causal loop diagram (CLD) of the power sector model

The power sector mainly has two different loops in the model. One loop is used for capacity planning based on 'forecast demand', and the other 'current gap'-based loop is designed to meet the demand at the current time scale, adjusting the plant load factors of thermal power plants (TPPs) and hydro plants. The seasonality and diurnal variation of the RE sources are considered while planning for the future capacity addition. Apart from variability, cost-based (LCOE-based) attractiveness of the resources plays a major role in determining the capacity addition of different resources. The plant load factors (PLFs) of TPPs and hydro plants are dynamically decided within the model. To avoid creating stranded TPP and hydro assets, the complete generation potential is considered while planning for future generation capacities.

The generation from RE sources is estimated based on the empirical capacity utilisation factors (CUFs). The TPP and hydro generation is used to meet the balance demand. We also consider the transmission and distribution (T&D) losses. The causal loop diagram for the power sector part of the model is shown in Figure A15.

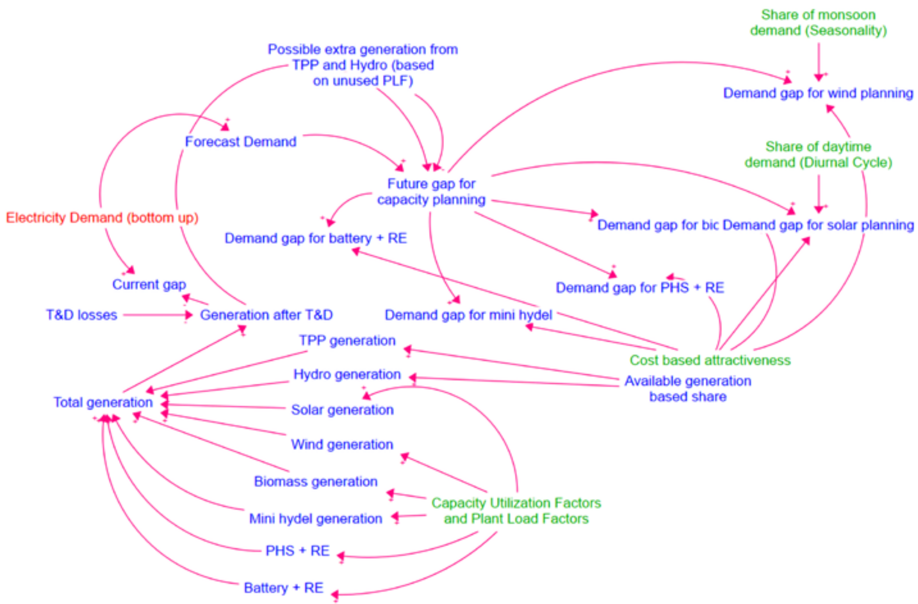


Figure A15: Causal loop diagram of the power sector part of the Namma SAFARI model

10.2.6.2. Addressing variability: seasonal and diurnal

RE sources such as solar and wind demonstrate strong seasonal and diurnal variability in Karnataka. The model is designed in such a way that the RE generation directly can only be used to meet the demand partly. However, in case of firmed-up RE, RE generation is stored in various storage systems (pumped hydro storage and battery) to address the demand at all hours of the day. The share of daytime as well as seasonal demand (0.57) is used to divide the annual demand into two parts—seasonal and diurnal demand and balance demand. The values are estimated based on the typical annual demand data of Karnataka.

$$\text{Demand gap}_{\text{variable}} = \text{Future gap} \times \text{Seasonal and diurnal share}$$

$$\text{Demand gap}_{\text{balance}} = \text{Future gap} - \text{Demand gap}_{\text{variable}}$$

10.2.6.3. Dynamic LCOE of coal-based TPPs

Estimation of the dynamic LCOE is a crucial part of our modelling. LCOE has two different parts: fixed and variable. While the capex cost contributes to the fixed charges, the fuel charges (if any) and regular maintenance costs are part of the variable cost. The following formula is used to estimate the dynamic LCOE endogenously in the model. Any decrease in PLFs would lead to an increase in LCOE.

$$\frac{Capital_{super} \times CRF_{TPP}}{Hrs_{year} \times PLF_{TPP}} + Coal\ cost_{domestic} \times \left(1 - \frac{Coal_{imported}}{Coal_{total}}\right) + Coal\ cost_{imported} \times \frac{Coal_{imported}}{Coal_{total}}$$

where

$$\frac{Capital_{super} \times CRF_{TPP}}{Hrs_{year} \times PLF_{TPP}} + Coal\ cost_{domestic} \times \left(1 - \frac{Coal_{imported}}{Coal_{total}}\right) + Coal\ cost_{imported} \times \frac{Coal_{imported}}{Coal_{total}}$$

$$Capital_{super} = \textit{Capital cost of super-critical thermal power plants}$$

$$CRF_{TPP} = \frac{Discount_{rate} \times (1 + Discount_{rate})^{Lifetime_{TPP}}}{((1 + Discount_{rate})^{(Lifetime_{TPP} - 1)})}$$

$$Coal\ cost_{imported} = \textit{Cost of imported coal per kg}$$

$$Coal\ cost_{domestic} = \textit{Cost of domestic coal per kg}$$

$$Hrs_{year} = \textit{Hours in a year (8760)}$$

10.2.6.4. Attractiveness estimation of different sources

The LCOE of electricity varies depending on the energy sources. SAFARI selects the energy sources depending on their LCOE values. This is done based on the attractiveness calculation of different electricity sources. The attractiveness changes depending on the availability of sources to meet a demand at a particular time, considering the day–night and seasonal differences. The following equations are used for attractiveness estimation, when all sources including solar and wind are available:

$$LCOE_{total} = LCOE_{TPP} + LCOE_{Hydro} + LCOE_{solar} + LCOE_{wind} + LCOE_{biomass} + LCOE_{minihydel} + LCOE_{RE+Battery} + LCOE_{RE+PHS}$$

$$Attractiveness_i = \frac{LCOE_{total}}{LCOE_i}$$

where i = TPP, hydro, solar, wind, biomass, mini-hydel, RE + Battery, or RE + PHS.

$$Attractiveness_{total} = \sum Attractiveness_i$$

$$Load\ share_i = \frac{Attractiveness_i}{Attractiveness_{total}}$$

$$\text{Demand gap}_{\text{variable}} = \text{Future gap} \times \text{Seasonal and diurnal share}$$

$$\text{Demand gap}_{\text{balance}} = \text{Future gap} - \text{Demand gap}_{\text{variable}}$$

where Load share_i is the share of demand taken up by different sources.

10.2.6.5. Data

The modelling horizon for *Namma* SAFARI is 2050, and the base year is 2015. The initial values for the stocks (i.e. 2015 values) and inputs for other variables like year-on-year capacity addition and capacity utilisation factors are provided based on the literature. The key data sources for the calibration of historical time periods are KPTCL and CEA.

The future peak demand is projected based on the EPS 20 dataset till 2032. A regression model based on the available historical data and the EPS forecast is used to project the peak demand data for future years.

10.2.6.6. Validation

Validation is a systematic process to establish model validity. It is a crucial but controversial facet of any model-based research, including system dynamics-based modelling work. The validation of a system dynamics-based model is a long and complex process involving both quantitative and qualitative tools. While the structural validity of a system dynamics (causal-descriptive) model is extremely important, validation of the back-casted results with reference to the historical values is also crucial.

To validate the electricity demand simulated by the *Namma* SAFARI model, the total simulated electricity demand till 2022 is compared with the historical electricity demand values from KPTCL. The simulated demand values are within reasonable accuracy range (8%) (Figure A16).

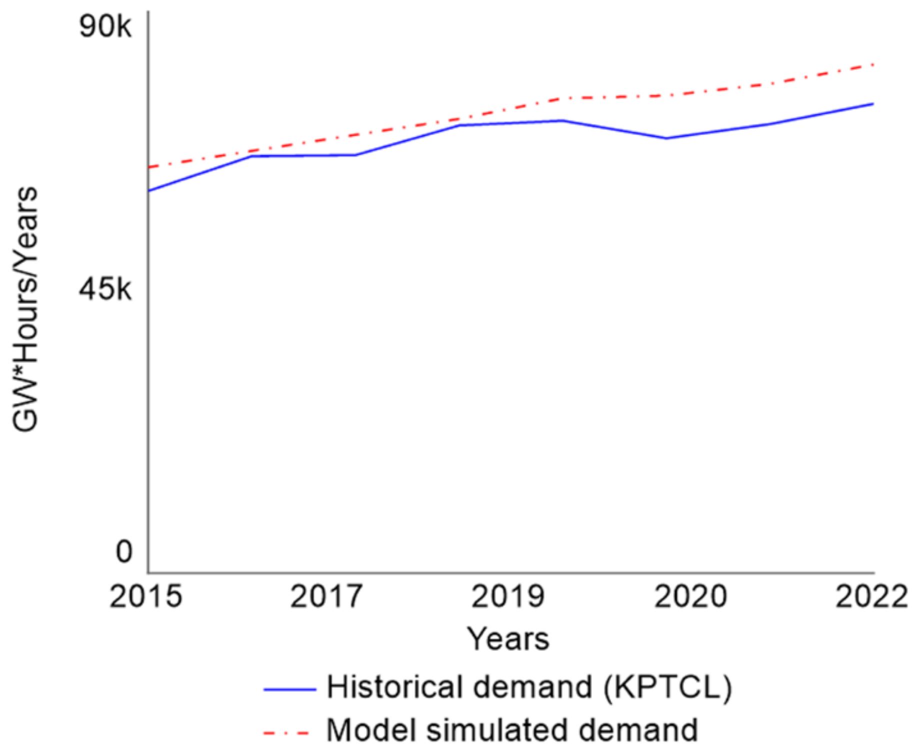
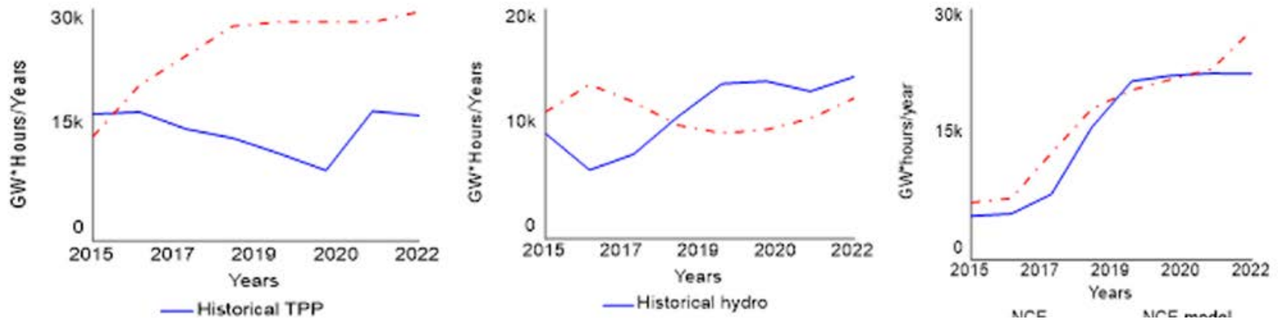


Figure A16: Validation of the total simulated electricity demand with respect to the historical electricity demand from KPTCL

We also validate the historical generation values from different energy sources simulated within the model with respect to the historical data from KPTCL (Figure A17). In the last decade, along with TPPs, hydro and non-conventional or RE plants (solar and wind) have played a significant role in the electricity generation landscape of the state. Figure A17 shows the comparison of TPPs, hydro, and non-conventional energy (NCE) generation values with the KPTCL historical dataset. While the model captures the growing annual electricity generation pattern for the NCE sources with reasonable accuracy (within 10% for most of the years), the model considerably overestimates the hydro and TPP generation.

TPPs have been facing challenges due to coal and water shortages in the state since the last decade. This might have impacted the recorded energy generation from the state TPPs. The generation from hydro plants depends on the rainfall in the state and might be impacted by the yearly rainfall variation. Further, a reduction in demand during the COVID-19 years (2020–2021) also might have impacted the generation. As the model could not capture these challenges, the model overestimates the generation from TPPs and hydro plants.



a) Comparison of TPP generation	b) Comparison of hydro generation	c) Comparison of non-conventional energy (NCE) generation

Figure A17: Validation of simulated non-conventional energy (NCE) and hydro generation with respect to the historical data (KPTCL)

CSTEP

CENTER FOR STUDY OF SCIENCE, TECHNOLOGY AND POLICY

Bengaluru

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

Noida

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

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