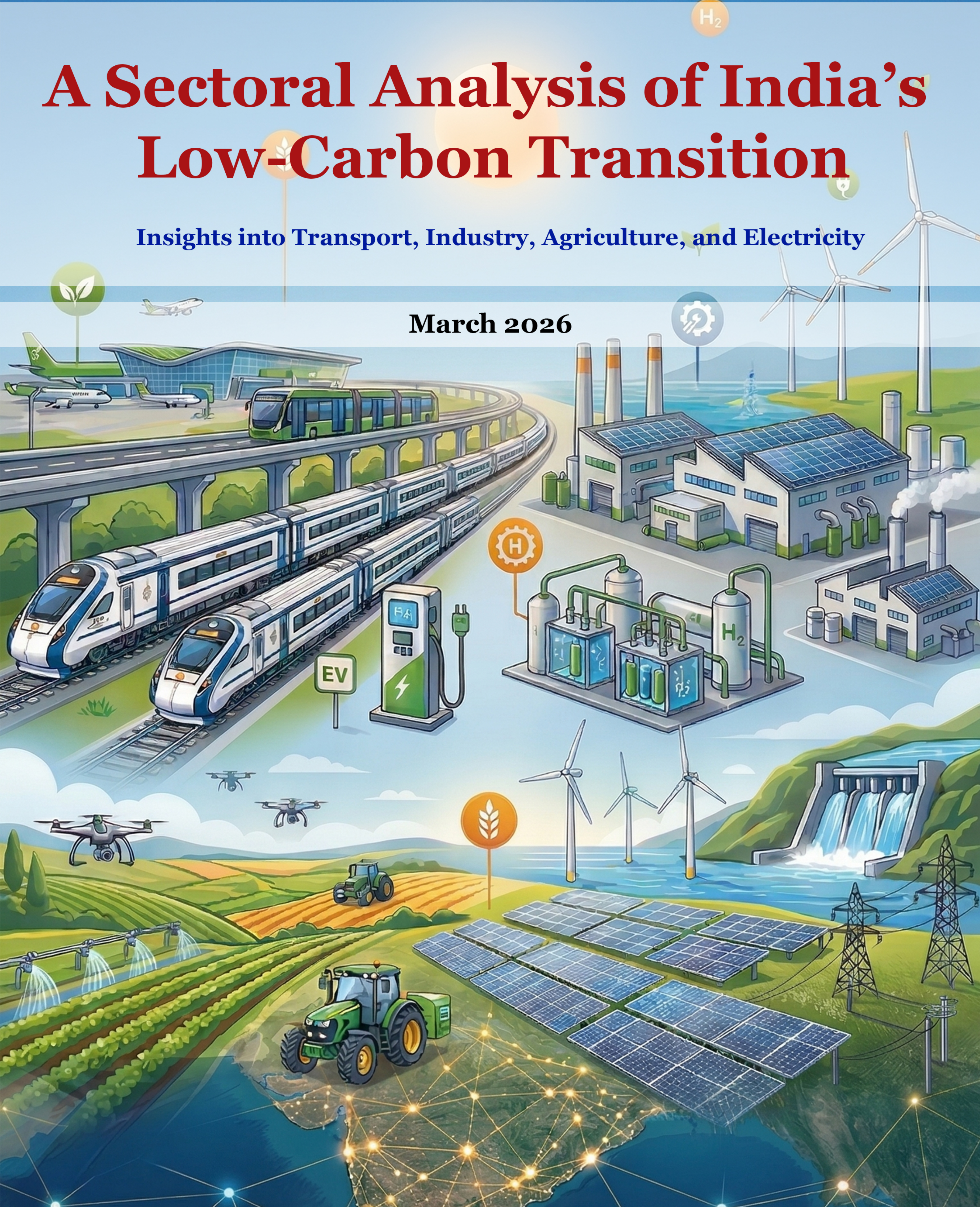
ASHOKA UNIVERSITY
CENTRE FOR A
People-centric
Energy Transition

A Sectoral Analysis of India's Low-Carbon Transition

Insights into Transport, Industry, Agriculture, and Electricity

March 2026



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About the Ashoka Centre for a People-centric Energy Transition (ACPET)

The Ashoka Centre for a People-centric Energy Transition (ACPET) is a research-focused, transdisciplinary centre within Ashoka University, India, established to drive a sustainable, equitable, and "people-centric" shift towards net-zero emissions. It bridges the knowledge gap in energy transition by collaborating with industry and government to create scalable solutions, covering areas like renewable energy, policy, and technology.

For further information about ACPET, please visit: acpet.ashoka.edu.in

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1. Introduction

India stands at a pivotal juncture in its development trajectory. As one of the world's fastest-growing major economies, the country is simultaneously pursuing rapid industrialisation, infrastructure expansion, and improvement in the living standards of its 1.4 billion people. This economic transformation, however, is deeply intertwined with energy consumption and greenhouse gas (GHG) emissions. India is currently the third-largest emitter of carbon dioxide globally and the third-largest consumer of primary energy, with fossil fuels continuing to dominate the energy mix.

Recognising the urgency of addressing climate change while safeguarding developmental priorities, India has made several ambitious commitments on the global stage. At COP26 in Glasgow, the Prime Minister announced the Panchamrit climate action plan, which includes achieving net-zero emissions by 2070, meeting 50 per cent of the country's energy requirements from renewable sources, reaching 500 GW of non-fossil electricity capacity by 2030, and reducing the carbon intensity of GDP by 45 per cent relative to 2005 levels. These commitments, formalised through India's updated Nationally Determined Contribution (NDC) under the Paris Agreement, set a clear long-term direction for the country's energy transition.

At the same time, India's developmental ambitions under the Viksit Bharat @2047 vision aim to transform the country into a developed nation by the centenary of its independence. Achieving this goal entails sustained high economic growth, large-scale infrastructure development, expansion of manufacturing capacity, and rapid increases in per capita income. These objectives will inevitably drive up demand for energy and materials across key sectors of the economy, such as transport, heavy industry, agriculture, and electricity.

This report presents an integrated assessment of India's energy demand and associated GHG emissions across three critical sectors: transport, industry, agriculture and energy supply and associated GHG emissions in the electricity supply sector. Using the Low Emissions Analysis Platform (LEAP), developed by the Stockholm Environment Institute, and complementary analytical methods, including system dynamics modelling and Gompertz-based demand saturation functions, the study develops sector-specific energy models. The LEAP-ACPET modelling framework provides a unified platform for examining how different combinations of policy interventions, technology transitions, and structural changes can shape future energy demand, supply and emissions trajectories through mid-century and 2070.

For each sector, the analysis constructs multiple scenarios representing varying levels of policy ambition. A Business-as-Usual (BAU) scenario captures the continuation of existing trends and policies. In contrast, alternate scenarios explore the impact of accelerated electrification, adoption of cleaner fuels and production technologies, improvements in energy efficiency, shifts in modal and material composition, the expansion of circular economy practices, increased penetration of renewables in electricity generation, and technological advancements in the power sector. In the transport sector, the model covers road, rail, and domestic air transport, and examines pathways driven by vehicle electrification, fuel-efficiency improvements, modal shifts, and biofuel blending. In the industry sector, the analysis spans five energy-intensive sub-sectors: iron and steel, cement, aluminium, caustic soda, and soda ash, and evaluates the role of technology substitution, green hydrogen, and expanded recycling. In the agriculture sector, the focus is on irrigation, pumping, and farm mechanisation, with attention to improving pump efficiency and to strategically substituting water-intensive crops with climate-resilient alternatives such as millets. In the electricity sector, the analysis assesses the impact of improved efficiency, increased renewables in electricity generation and technological advancements on associated GHG emissions. The sources of generation considered are coal, gas, solar, wind, biomass, waste, small hydro, large hydro, and nuclear.

The temporal scope of the analysis extends from a base year of 2019–20 (for transport), 2022 (for industry and agriculture) through 2047–50, and base year of 2024 (for electricity supply) through 2070, aligning with both the Viksit Bharat planning horizon and the mid-century timeframes as well as long-term horizon, commonly adopted in national energy modelling exercises. All GDP values used in the model are expressed in constant 2011–12 INR, and population projections are sourced from the United Nations World Population Prospects.

The overarching objective of this report is to generate evidence-based, policy-relevant insights that can inform India's energy transition strategy. By quantifying how alternative development pathways affect energy demand, energy supply and emissions across sectors, the analysis aims to identify priority areas for intervention, highlight the scale of transformation required to meet national climate commitments, and support coordinated planning across the energy, electricity, transport, industrial, and agricultural domains. The findings are intended to serve policymakers, researchers, and practitioners engaged in designing India's transition towards a low-carbon, energy-secure, and developed economy.

2. Need for Study

India's energy landscape is undergoing rapid transformation, driven by the twin imperatives of sustaining high economic growth and fulfilling ambitious climate commitments. The country's energy demand is projected to grow substantially over the coming decades as infrastructure expands, industrial output increases, urbanisation accelerates, and per capita income rises. At the same time, India's commitments under the Paris Agreement, including achieving net-zero emissions by 2070 and reducing the carbon intensity of GDP by 45 per cent by 2030, require a fundamental restructuring of how energy is produced and consumed across all sectors of the economy.

Despite the availability of broad national strategies and sectoral targets, India currently lacks a comprehensive, integrated, and data-driven analytical framework that systematically links energy demand and supply projections with technology transitions, policy interventions, and structural changes across its major energy-consuming and producing sectors.

In the transport sector, energy consumption is rising rapidly, driven by increasing vehicle ownership, expanding freight movements, and continued dependence on imported petroleum products. The sector accounts for nearly 19 per cent of India's final energy use and approximately 14 per cent of its energy-related GHG emissions. While several policy measures, such as the FAME scheme for electric vehicles, CAFÉ fuel-efficiency norms, and biofuel blending targets, have been introduced, India still lacks a clear, data-driven low-carbon development roadmap for the transport sector to evaluate the long-term impacts of these interventions through systematic modelling and scenario analysis.

In the industrial sector, the challenge is equally pressing. Industry accounts for approximately 35 per cent of total final energy consumption and nearly 30 per cent of national GHG emissions. Energy-intensive sub-sectors such as iron and steel, cement, and aluminium are expected to see substantial increases in output as India builds out its infrastructure and manufacturing base. Under business-as-usual conditions, industrial emissions could escalate to approximately 2,657 million metric tonnes of CO_2 equivalent by 2050. Although prior studies have explored trends in industrial energy consumption, there is a continuing need for scenario-based analyses that explicitly reflect national policy objectives and long-term transition goals. Such approaches can provide more policy-relevant insights to support strategic planning and decision-making.

In the agriculture sector, energy demand is driven by irrigation pumping and farm mechanisation, which together account for the bulk of direct energy use. Agriculture consumes roughly 17 to 20 per cent of India's total electricity, with irrigation pump sets numbering over 30 million and average pump efficiencies remaining below 40 per cent. The expansion of mechanisation and groundwater-based irrigation is expected to push energy demand further upward, yet the sector has received comparatively less attention in integrated energy modelling exercises.

In the electricity sector, demand is projected to increase nearly fifteenfold compared to 2022 consumption levels. This growth is driven by rapid urbanisation, rising per capita incomes, and the emergence of new demand centres such as data centres, electric mobility, and increased cooling needs resulting from global warming. The anticipated surge in electricity demand has significant implications for how this electricity is generated, particularly in terms of the evolving mix of fossil and non-fossil energy sources, associated emissions from power generation, and the scale of infrastructure development required.

This study addresses these gaps by developing integrated, multi-sectoral energy demand and supply models using the LEAP-ACPET modelling framework. By combining bottom-up technology representation with scenario-based policy analysis across transport, industry, agriculture, and electricity, the study provides a unified platform for assessing how alternative development pathways shape future energy consumption, generation and emissions trajectories. The use of saturation-based demand modelling, system dynamics, and technology-explicit scenario construction ensures that the analysis moves beyond incremental assessments to examine the implications of deep structural transformation.

The findings of this study are intended to support evidence-based policymaking by identifying the scale and nature of interventions required to align India's sectoral energy demand and supply with its long-term climate goals, while ensuring that the country's developmental objectives under the Viksit Bharat @2047 vision are not compromised. In doing so, the study provides a national perspective by presenting sectoral analyses within a consistent analytical context.

3. Macro-Economic Parameters and Assumptions

The energy demand and supply projections developed in this report rest on a set of macro-economic assumptions that define the broader context within which sectoral energy consumption evolves. These parameters, primarily Gross Domestic Product (GDP) and population, serve as the fundamental drivers of transport activity, industrial output, agricultural mechanisation, electricity demand, and overall energy demand. Ensuring consistency in these assumptions across sectors is essential for the coherence and comparability of the scenario results.

Gross Domestic Product (GDP)

All GDP values used in the model are expressed in constant 2011–12 Indian Rupees (INR) to eliminate inflationary effects and enable consistent comparisons of real economic growth over time. The choice of 2011–12 as the base year for GDP measurement is aligned with national accounting practices established by the National Statistical Office (NSO). Historical GDP data from 2000 to 2025 are sourced from the Reserve Bank of India's Database on Indian Economy, specifically from the Macroeconomic Aggregates at constant prices series. For the projection period from 2026 to 2050/2070, GDP trajectories are derived from NITI Aayog's India Energy Security Scenarios (IESS) 2047, Version 3, and internal assumptions are made for 2070, which provide internally consistent economic growth projections aligned with India's long-term developmental planning under the Viksit Bharat @2047 vision, which envisions India as a USD 30 trillion economy.

GDP serves as a primary driver in the modelling framework across all four sectors. In the transport sector, GDP per capita is used in conjunction with population to estimate total passenger and freight transport demand through a saturation-based logistic function, reflecting the observed correlation between economic development and mobility growth. In the industry sector, GDP growth underpins the Gompertz-based demand projections for key materials such as steel, cement, and aluminium, capturing the non-linear relationship between income growth and material consumption. In the agriculture sector, GDP growth is implicitly reflected through assumptions on mechanisation intensity, irrigation expansion, and structural transformation in farming practices. In the electricity sector, it is the key macro-economic variable that determines the future growth in electricity demand in India.

Population

Population data from 2000 to 2024 is sourced from the Reserve Bank of India's Database on Indian Economy. For the projection period from 2025 to 2070, population estimates are drawn from the IESS 2047 Version 3 and the United Nations Population Division's World Population Prospects. Population, together with GDP, determines GDP per capita, which is the key variable linking macro-economic growth to sectoral energy demand and supply in the modelling framework. The saturation-based transport demand model, for instance, uses the logarithmic relationship between GDP per capita and per capita mobility to project future passenger and freight demand, with saturation limits set at 16,000 passenger-kilometres per capita for passenger transport and 10,000 tonne-kilometres per capita for freight transport, based on observed benchmarks from developed economies.

GHG Emission Factors

Greenhouse gas emission factors used across all sectors are sourced from the IPCC 2006 Guidelines. These emission factors are entered exogenously in the model's Current Accounts and remain constant across all scenarios to ensure comparability of results. Emission factors are applied to the estimated energy demand and supply by fuel type to derive total CO_2 and CO_2-equivalent emissions for each sector, mode, and technology pathway.

Temporal Scope and Base Year

The model's temporal coverage varies across sectors but broadly aligns with mid-century and long-term planning horizons. The transport sector model spans from 2019–20 to 2049–50, using 2019–20 as the base year, selected as the most recent pre-pandemic year with comprehensive and reliable transport activity data. The industry sector model uses 2022 as the base year and projects through 2047, aligned with the Viksit Bharat vision. The agriculture sector model similarly covers the period from 2020 to 2047. The electricity sector covers the period from 2024 to 2070. In all cases, projections commence from the respective base years and extend through the terminal year, with energy demand, supply and emissions estimated annually.

These macro-economic parameters and data sources are held constant across all scenarios within each sector. Differences between the Business-as-Usual and alternate scenarios arise exclusively from changes in technology shares, efficiency assumptions, modal composition, and policy-driven structural shifts, not from variations in underlying economic or demographic trajectories. This ensures that scenario comparisons isolate the impact of sector-specific interventions against a common macro-economic backdrop.

4. Energy Demand & Associated GHG Emissions

This section presents a comprehensive assessment of India’s energy demand and the associated greenhouse gas (GHG) emissions. The national energy landscape is traditionally defined by five primary demand-side pillars: Transport, Industry, Agriculture, Residential Buildings, and Commercial Buildings. Together, these segments drive the overwhelming majority of India's final energy consumption and constitute the principal sources of energy-related carbon dioxide emissions. Understanding the unique drivers of each sector, from the cooling requirements of an urbanising population to the material intensity of a growing industrial base, is essential for aligning India's developmental aspirations under Viksit Bharat @2047 with its 2070 Net Zero commitment.

While all five sectors are integral to the national energy balance, this report focuses its detailed analytical modelling on the three sectors that represent the most significant for the long-term transition: Transport, Industry, and Agriculture.

This report prioritises these three segments (covered in Sections 4.1 through 4.3) due to their complex technological structures and their central role in India's industrialisation and food security.

Transport Sector: Examining road, rail, and air transport, this analysis utilises the ASIF (Activity–Structure–Intensity–Fuel) framework. The sector currently accounts for nearly 19 per cent of final energy use, with road transport responsible for over 90 per cent of those emissions. The study explores how accelerated electrification and modal shifts toward public transport can decouple mobility from fossil fuel consumption.

Industry Sector: Focusing on energy-intensive sub-sectors, iron and steel, cement, and aluminium, the analysis tracks how structural shifts can alter long-term demand. These industries collectively account for approximately 35 per cent of final energy consumption. The model investigates deep emission reduction levers such as hydrogen-based steelmaking, clinker reduction in cement, and the expansion of secondary metal production through circular economy frameworks.

Agriculture Sector: This sector focuses on the energy requirements for irrigation, pumping and farm mechanisation, which together account for roughly 17 to 20 per cent of India's total electricity consumption. The analysis adopts a bottom-up, equipment-based approach to explore how technology performance and strategic crop substitution (the Food-Energy-Water nexus) can serve as a structural demand-side management tool.

Across these sectors, a consistent finding emerges: incremental efficiency improvements within existing structures yield only modest reductions. True alignment with India's climate goals requires a managed shift in production processes, modal composition, and material flows. The following sub-sections provide the detailed methodology, scenario results, and policy insights for the transport, industry, and agriculture sectors.

4.1. Transport Sector

Introduction

As an economy grows and population levels rise, demand for the movement of people and goods increases. This increased mobility demand, in turn, drives up transportation energy demand, which is still largely met by fossil fuels (India Energy & Climate Centre, 2024). In India, the transport sector is one of the largest energy consumers, accounting for nearly 19 % of final energy use in 2020 (CEEW, 2022). It accounts for nearly 90% of the country's total crude oil demand, most of which is met through imports (India Energy & Climate Centre, 2024). This continued reliance on imported crude oil not only raises concerns about India's energy security but also adds to environmental pressures, such as rising greenhouse gas emissions and worsening air quality.

India aims to achieve a net-zero economy by 2070 and reduce the emission intensity of its GDP by 45% by 2030 as part of its commitment to emissions reduction under the Paris Agreement. As part of these commitments, India also aims to meet 50 per cent of its energy requirements from renewable energy sources and reach 500 GW of non-fossil energy capacity by 2030 (Government of India, Updated First Nationally Determined Contribution Under the Paris Agreement, 2022). As a major source of greenhouse gas emissions, accounting for 14 per cent of the country's total energy-related greenhouse gas emissions (NITI Aayog, 2021), of which road transport alone accounts for more than 90%, the transport sector plays a vital role in achieving these goals. Thus, identifying and modelling pathways for reducing emissions from the transport sector is critical to achieving India's climate goals, such as becoming a net-zero economy by 2070. While several broad strategies exist, India still lacks a clear, data-driven roadmap for low-carbon development of the transport sector that is grounded in systematic data analysis and modelling to prioritise interventions, evaluate their long-term impacts, and align multiple strategies into coherent future pathways that link technology, policy, and behavioural shifts in a consistent direction toward a low-carbon transport future. The strategies that have been identified for reducing emissions from the transport sector are as follows:

- **Electrification** across all major vehicle categories.
- **Adoption of cleaner fuels** and gradual phase-down of conventional fossil fuels.
- **Improvements in fuel economy** and overall vehicle efficiency.
- **Modal shift** from private vehicles to public and shared transport.
- **Biofuel blending** targets include ethanol, biodiesel, and compressed biogas (CBG) in petrol, diesel, and CNG.

Over the past decade, several major policy measures have been introduced to operationalise these strategies:

1. **The Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) scheme,** launched under the National Electric Mobility Mission Plan, promotes the adoption of electric and hybrid vehicles across segments (two-wheelers, three-wheelers, passenger cars, and buses) and supports the development of charging infrastructure. FAME Phase-II, operational since 2019 and extended to 2024, allocates ₹10,000 crore for demand incentives like financial subsidies and tax rebates and infrastructure deployment (Ministry of Heavy Industries, 2023).
2. **The Corporate Average Fuel Efficiency (CAFÉ)** regulations mandate that automobile manufacturers achieve a fleet-average fuel efficiency of 130 g CO_2/km under Phase I (implemented in 2017) and 113 g CO_2/km under Phase II (effective from 2022), thus demonstrating that the standards are becoming more stringent over time (Bureau of Energy Efficiency, 2020).
3. India has also set some targets for emissions reduction from the sector, such as the target of achieving 45% share of rail in freight by 2030 under the National Rail Plan (Ministry of Railways, 2022) and the EV30@30 target that aims to achieve 30% of the sales to be EVs by 2030 (Ministry of Heavy Industries, 2025). These targets represent shifts in modal and fuel shares that act as key means to achieve emission reduction, since shifting freight movement to energy-efficient

rail transport and increasing the share of clean alternative technologies help lower overall transport sector emissions. There are also some targets for biofuel blending under the National Policy on Biofuels (Ministry of Petroleum & Natural Gas, 2018):

- Ethanol (20% by 2030 – already achieved nationwide in 2025)
- Biodiesel (5% by 2030)

Together, these measures represent India's early steps toward a lower-emission transport future, but significant implementation and coordination challenges remain.

This study explores potential pathways to reduce emissions from India's transport sector. It aims to inform policy decisions by assessing how different combinations of strategies could shape future energy use and emissions trajectories in line with India's national commitments. The analysis is conducted using the Low Emissions Analysis Platform (LEAP), an energy-modelling tool developed by the Stockholm Environment Institute (SEI). LEAP is particularly suited for this study as it provides a transport-ready structure that enables detailed modelling of technology and fuel interventions, captures both greenhouse gases and air pollutants to assess co-benefits, and remains user-friendly and scalable for national and subnational analyses. It has been widely applied in developing countries, including in the preparation of over 30 NDC submissions to the Paris Agreement. LEAP's interoperability with other models, such as CGE, GAINS, and WEAP, facilitates integrated energy–environment planning. At the same time, its low initial data requirements and built-in Technology and Environmental Database (TED) enable the easy incorporation of emission factors and the creation of scenarios. Through this platform, future energy demand and emissions are estimated up to 2050, providing insights to support long-term energy planning and guide policy priorities for building a low-emission transport system.

Objectives

This study aims to explore possible pathways to a low-carbon, energy-efficient future for India's transport sector, developed against the backdrop of India's long-term vision to achieve Net Zero emissions by 2070 and the developmental goals under Viksit Bharat @2047. The objectives of the study are two-fold:

1. **Quantify future energy demand and emissions trajectories**
   Estimate the transport sector's energy use and greenhouse gas emissions through 2050 under two contrasting scenarios:

- a **Business-as-Usual (BAU)** pathway reflecting continuation of current trends and policies, and
- An **Ambitious** pathway that captures the combined effects of key transition strategies, such as vehicle electrification, adoption of cleaner fuels, improvements in fuel efficiency, and modal shifts towards cleaner modes of transport.

2. **Derive policy insights for a low-emission transport transition**

Draw on the scenario outcomes to identify policy measures that can guide India's transport system towards a sustainable, low-emission future in line with national climate commitments, such as achieving net-zero by 2070.

To achieve these objectives, the study adopts the following methodological framework:

Methodology

This study employs a hybrid modelling framework, termed 'hybrid' because it links top-down projections of transport activity with bottom-up estimation of energy use and emissions, integrating macroeconomic drivers with detailed technological and modal characteristics. Based on the correlation between per capita mobility and GDP per capita (Dhar & Shukla, 2015), the top-down component estimates total passenger and freight transport demand using GDP and population growth as primary macroeconomic drivers, along with per capita transport demand saturation limits that reflect practical constraints on how much travel can increase over time. Passenger mobility demand has saturated in developed countries such as the US, Germany, Japan, and South Korea (Dargay et al., 2014). This is rooted in the idea that as income and population levels rise, people travel more, but this trend tapers off once a certain threshold is reached. A similar saturation limit is assumed for freight mobility, grounded in evidence that freight transport intensity (tonne-km per GDP) stabilises or declines as economies become service-oriented (ITF-OECD, 2024). This implies that freight activity per capita eventually reaches a steady state, and the model integrates this behaviour to capture the slowing growth of transport demand in mature economies in line with India's Viksit Bharat vision for 2047.

The **bottom-up component** disaggregates transport activity by vehicle category and technology to estimate energy demand and GHG emissions. This includes:

- Detailed vehicle segmentation (cars, buses, trucks, two-wheelers, etc.) to capture variation in usage and energy intensity
- Transitions in technology mix, including shifts from internal combustion engines (ICEs) to hydrogen fuel cell vehicles (FCVs), electric vehicles (EVs), and other alternative fuels
- Mode and technology-specific fuel/energy intensities

The model further identifies five key levers shaping future energy and emissions trajectories: GDP and population growth, saturation limits on per capita demand, changes in the modal split, technology mix transitions, and improvements in vehicle fuel efficiency. These levers form the basis for scenario analysis, enabling exploration of alternative pathways and supporting policy recommendations for a cleaner, more energy-efficient transport sector.

The LEAP–ACPET transport model captures energy demand and greenhouse gas (GHG) emissions from India's transport sector across three primary modes: road, rail, and air. Each mode is further divided into passenger and freight sub-modes to reflect the distinct activity patterns and energy-use characteristics of these segments. For road transport, passenger activity includes cars, two-wheelers, buses, and other vehicle types, while freight activity is represented by heavy and light commercial vehicles. The model also includes heavy commercial vehicles (HCVs) and medium commercial vehicles. Water transport has not been included in the current version of the model due to limited data availability, particularly for coastal shipping.

The model's temporal coverage spans from 2019–20 to 2049–50, using 2019–20 as the base year. The base year has been selected to align with the most recent year for which comprehensive, pre-pandemic transport activity and energy consumption data are available across official sources such as MoRTH, the Ministry of Railways, and the Directorate General of Civil Aviation. The terminal year 2049–50 corresponds to mid-century planning horizons commonly adopted in national energy and climate modelling exercises and aligns with India's long-term vision of Viksit Bharat @2047. Energy demand and emissions are estimated annually over this period. Five fuel types, gasoline/petrol, diesel, compressed natural gas (CNG), electricity, and hydrogen fuel cells (FCVs), are represented in the technological pathways, enabling simulation of transitions in the fuel and technology mix.

It is important to note that the air transport component of the model covers only the domestic aviation sector. This ensures consistency with the model's national scope and avoids overlap with international aviation emissions, which are accounted for separately in global inventories. Figure 1 illustrates the hierarchical structure of the transport model, showing the classification of modes, sub-modes, and vehicle types across the transport sector.

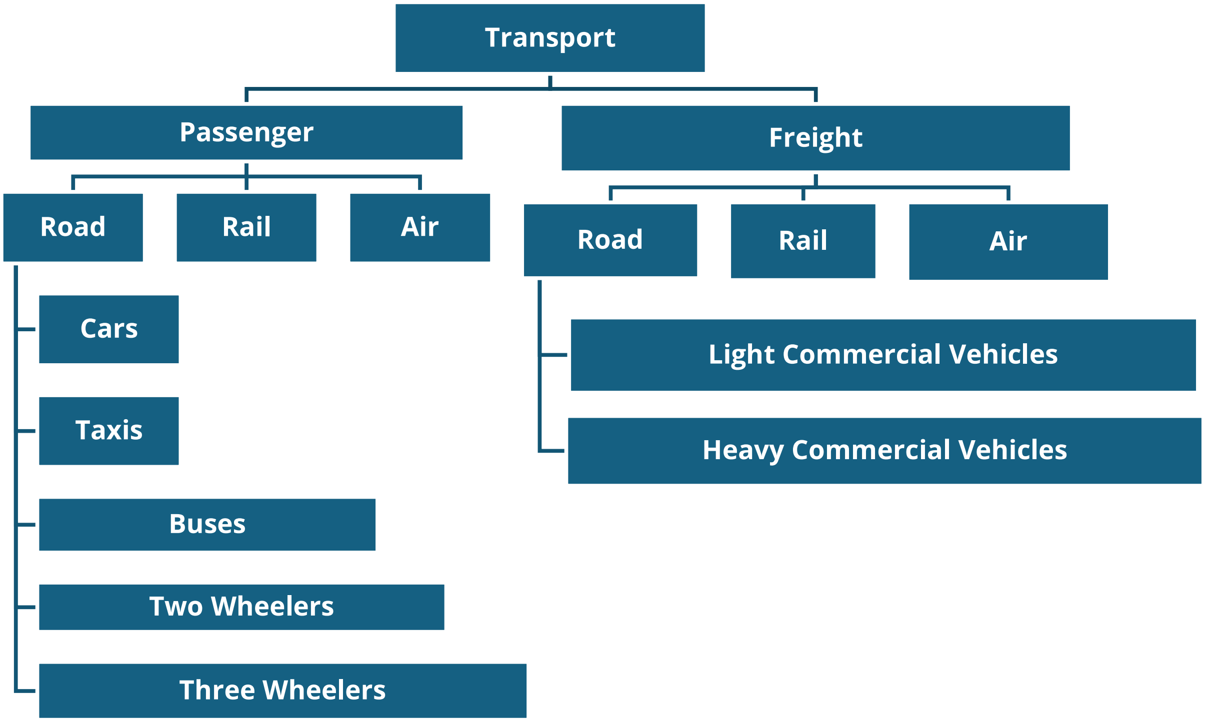


Figure 1: Categorical Disaggregation of the Transport Sector in the Model

The LEAP–ACPET transport model applies the ASIF (Activity–Structure–Intensity–Fuel) framework to systematically estimate energy demand and GHG emissions in India's transport sector. Originally conceptualised by Schipper et al. (1999) and used in the UNFCCC (2018) Compendium on GHG Baselines and Monitoring – Passenger and Freight Transport, the ASIF approach decomposes total emissions into four core components:

$$GHG\ Emissions = A \times S \times I \times F$$

where:

- **A (Activity):** The total volume of passenger or freight transport, typically measured in passenger-kilometres (PKM) and tonne-kilometres (TKM). This reflects the scale of transport demand driven by demographic and economic factors.
- **S (Structure):** The modal composition of transport activity across road, rail, and air, as well as the distribution across vehicle types within these modes. Changes in modal shares (e.g., shifting from private vehicles to public transport) directly influence emissions outcomes.
- **I (Intensity):** The energy intensity of transport modes and vehicle types, expressed as energy consumption per kilometre travelled. This captures technological improvements in fuel efficiency over time.
- **F (Fuel):** The emission factor associated with different fuel types, measured in tonnes per unit of energy. This component reflects the carbon intensity of the energy mix, including transitions to cleaner fuels like electricity or hydrogen.

The ASIF framework (Schipper et al., 1999) provides a robust, transparent analytical structure for examining how policy interventions and technological changes can influence each component and thereby reduce sectoral GHG emissions. It is widely used in transport energy modelling studies for its ability to isolate the contribution of activity growth, modal shifts, technology adoption, and fuel transitions to total emissions.

In this study, the ASIF framework is operationalised within LEAP by linking demographic and macroeconomic projections (GDP and population) to transport demand, disaggregating it by mode, vehicle type, and technology mix, and combining it with energy intensities and fuel-specific emission factors.

Figure 2 illustrates this process flow, showing the relationships between key inputs (e.g., GDP, population, modal split, fuel efficiency) and outputs (energy demand and GHG emissions).

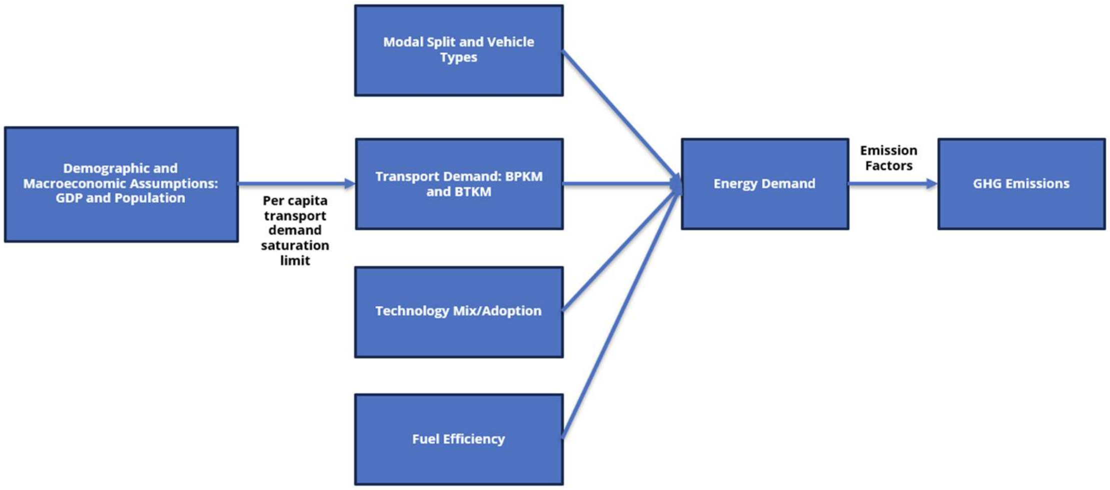


Figure 2: Flow of LEAP's Calculations

Historical Transport Demand Estimation

Historical transport demand was estimated for road, rail, and air modes over 20 years from 1990-00 to 2019-20. The methodology applied for each mode is described below:

1. Road Transport

The historical road transport demand was calculated using the following equation:

$$BPKM\ or\ BTKM\ = On - road\ vehicles\ \times\ Average\ annual\ distance\ travelled\ \times\ Occupancy\ or\ Payload$$

Source: ACPET LEAP Model

This yielded a total of billion passenger-kilometres (BPKM) for passenger vehicles and billion tonne-kilometres (BTKM) for freight vehicles.

- On-road vehicles were estimated from registered vehicle data reported by the Ministry of Road Transport and Highways (MoRTH) using assumed vehicle lifetimes.
- Average annual distance travelled, and occupancy/payload factors were obtained from secondary literature.

Detailed assumptions for vehicle life, annual distance travelled, occupancy, and payload are provided in the Appendix.

This estimation was carried out separately for all road vehicle categories: cars, taxis, buses, two-wheelers, three-wheelers, light commercial vehicles, and heavy commercial vehicles.

The total road passenger and freight activity, expressed in BPKM and BTKM, respectively, was then obtained by aggregating the values across these categories.

2. Rail Transport

Data on rail transport activity were obtained directly from the Indian Railways Yearbook, which provides annual statistics on passenger and freight movements.

3. Air Transport

Data on air transport activity were sourced from the Directorate General of Civil Aviation (DGCA) Yearly Statistics, covering domestic passenger-kilometres and freight movements within India.

Base year data in the model

This provides the base year 2019-20 data for total transport demand broken down by passenger and freight, % (percentage) share of modes under passenger and freight, % (percentage) share of categories under road (passenger and freight), and % (percentage) share of fuels represented under each category across all modes (passenger and freight) are assumed based on literature review/ review of existing models.

The model uses 2019–20 as the base year, representing the last pre-pandemic year with complete and reliable transport activity and fleet data across modes. Projections commence from 2020–21, which coincides with the onset of COVID-19; however, the pandemic's short-term disruptions are not explicitly modelled. The projections instead represent the long-term evolution of transport energy demand based on structural factors such as economic growth, vehicle ownership, and technology transitions, without accounting for the temporary mobility restrictions and demand shocks experienced during 2020–21 and 2021–22.

Fuel consumption per kilometre for the base year is calculated using the following relation:

$$Final\ Energy\ Intensity\ or\ Fuel\ Efficiency\ (l/km\ or\ kwh/km)\ =$$
$$1/\ (Occupancy\ (passenger)\ or\ Payload\ (freight)\ \times\ Vehicle\ Mileage\ (km/litre\ or\ km/kWh))$$

Detailed assumptions regarding vehicle mileage are provided in the Appendix.

This provides estimates of fuel consumption (per-kilometre consumption multiplied by activity level), which are then converted to energy demand using standard fuel-to-energy conversion factors based on the energy content of each fuel type.

The resulting energy demand value is multiplied by standard emission factors (from secondary sources such as IPCC) to estimate total CO_2 emissions across all modes, vehicle types/categories, and fuels for the base year, i.e., 2019-20.

Base-year results have been cross-checked against publicly available projections, such as NITI Aayog's India Energy Security Scenarios (IESS) 2047, TERI's Roadmap for India's Energy Transition, and CEEW's India Transport Energy Outlook, to ensure that initial model behaviour falls within credible ranges. These ranges are discussed in the Model Results Validation section.

Projection for Future Transport Demand

Future transport demand in India was projected using a saturation-based methodology that links economic growth and population increase (GDP per capita) with passenger and freight mobility. The approach is grounded in observed trends in developed countries, where transport demand tends to grow with GDP and population up to a certain level, then saturates.

1. Economic Basis of Mobility Growth

Passenger transport demand, measured in passenger-kilometres (pkm), is closely correlated with a country's economic activity. Based on the correlation established between the two by Dhar and Shukla (2015), a logarithmic relationship was assumed between per capita GDP and per capita passenger transport demand:

$$z = LN\left(\frac{S}{(S_o - S)}\right) = LN\left(\frac{GDP}{Capita}\right) * a + b$$

Where:

- S = per capita passenger transport demand (pkm)
- S_0= saturation limit (maximum per capita demand)
- a = regression coefficient
- b = regression constant

The assumption behind this model is that as income and population levels rise, people travel more, but this trend eventually plateaus once a certain level of development is reached. Empirical evidence from developed economies shows that inland passenger mobility generally falls within 12,000–20,000 pkm per capita, for example:

- **United Kingdom:** Domestic mobility remained close to **12,500 pkm/person** from 1990 to 2015 (DDPP–UK, 2017).
- **OECD North America:** Mobility was approximately **20,800 pkm/capita** in 2005 (Greenpeace & EREC, 2008).
- **OECD Europe:** Mobility was approximately **12,900 pkm/capita** in 2005 (Greenpeace & EREC, 2008).

In this model, a saturation level of **16,000 pkm/capita** was assumed for passenger demand, based on convergence with observed values in high-income countries and aligned with India's expected development trajectory.

For historical and projected GDP and population data, data were taken from the **Handbook of Statistics on the Indian Economy** and **NITI Aayog's IESS 2047 (Version 3), respectively**. All GDP values are in constant 2011–12 INR to eliminate inflationary effects and enable consistent comparisons of real economic growth over time. The 2011–12 base year is used in alignment with national accounting practices established by the National Statistical Office (NSO).

2. Freight Transport Demand

A similar methodology was used for projecting freight transport demand (in tonne-kilometres per capita), assuming a saturation level of **10,000 tkm/capita**. This is aligned with benchmarks from China, where per capita freight demand reached approximately 10,390 tkm in 2020 (OECD, 2023).

3. Use of Logistic S-Curve for Projections

$$z = LN\left(\frac{S}{(S_o - S)}\right) = LN\left(\frac{GDP}{Capita}\right) * a + b$$

Using the equation above, the parameters **a** and **b** were estimated by regression using historical data from 1990-00 to 2019-20. The following logistic sigmoid function was used to project future per capita transport demand, separately for passenger and freight:

$$S = \left(\frac{S_o}{1 + e^{-z}}\right)$$

This approach generates an S-curve reflecting slow initial growth, rapid mid-stage growth, and eventual saturation.

- ➔ The total transport demand is calculated as the sum of passenger and freight transport demand for the historical and projected timeframes.

4. Estimating Energy Demand and GHG Emissions

After projecting total passenger and freight transport demand till 2049-50, for the projected timeframe 2020-21 to 2049-50, using the methodology used for base year data, the model estimates fuel consumption, which is then used to derive energy demand and CO_2 emissions, corresponding to the projected transport demand across different modes, categories, and fuel types, under different scenarios with varying assumptions regarding modal shares, efficiency improvements and transition in technology/fuel mix (shares).

*Fuel/Energy Demand = Activity level (BPKM or BTKM) * Final Energy Intensity (fuel consumed per kilometre)*

The scenarios and their assumptions are discussed in the upcoming sections.

This step-by-step approach helps the model show how changes in modal shares, changes in vehicle technology shares, and improvements in fuel efficiency affect fuel use and emissions over time.

Scenario Description

This study explores plausible pathways for emissions reduction in India's transport sector through 2050 by creating two different scenarios:

1. **Business-As-Usual (BAU):** The Business-as-Usual scenario, commonly referred to as BAU, assumes that current trends and policies continue through 2050 without any new interventions to mitigate emissions from the sector.
2. **Ambitious (AMB):** The Ambitious scenario assumes aggressive mitigation efforts to achieve greater emissions reductions within the sector.

Both scenarios are developed using the same set of analytical levers, but these levers operate differently across them.

The levers are as follows:

1. **Modal shifts** among road, rail, and air transport
2. **Shifts in shares of categories** within road transport (for both passenger and freight)
3. **Changes in the technology mix** under each vehicle category
4. **Annual fuel efficiency improvements**

The Business-as-Usual (BAU) scenario projects a trajectory in which activity-driven energy demand and emissions continue to grow through 2050, with only marginal improvements from existing policies, schemes, and targets. Private transport remains the preferred mode of travel, while the adoption of cleaner fuels such as electricity and hydrogen remains limited. The policy environment is characterised by incremental progress, such as gradual uptake of electric vehicles, moderate improvements in fuel efficiency, and slow uptake of public transport infrastructure.

In contrast, the Ambitious (AMB) scenario assesses the impact of a greater policy push and a higher share of clean mobility technologies. This pathway assumes accelerated electrification across all vehicle segments, higher deployment of hydrogen fuel cell vehicles (FCVs), and stronger modal shifts from private to public transport. As a result, the scenario yields a future trajectory with lower overall energy demand and reduced sectoral emissions by 2050.

Policy Context: Fuel Efficiency & Electrification

India has implemented several measures to improve vehicle fuel efficiency and is actively accelerating the adoption of Electric Vehicles (EVs) through initiatives like CAFÉ and FAME. Similarly, the Corporate Average Fuel Efficiency (CAFÉ) norms were notified by the Government of India in 2017 under the Energy Conservation Act, 2001. The primary aims of these norms are to improve vehicle fuel efficiency and reduce emissions. These rules apply to all passenger vehicles (petrol, diesel, CNG, LPG, hybrid, and electric) weighing less than 3500 kg. Rather than being applied to a single vehicle's fuel efficiency, these rules set a limit on the average fuel consumption of all vehicles sold by a manufacturer (like Maruti) in a year. The government measures the average fuel consumption per 100km and average CO_2 emissions under standard lab conditions.

The norms are as follows:

CAFÉ norms	Average CO2 emissions	Average fuel consumption	Average curb weight	Effective year
Stage 1	Less than 130g/km	Less than 5.5L/km	1037 kg	2017-18 onwards
Stage 2	Less than 113g/km	Less than 4.7L/km	1082 kg	2022-23 onwards

Table 1: CAFÉ norms

With increasingly stringent CAFÉ standards and a trend toward heavier passenger vehicles, manufacturers are developing more fuel-efficient, low-emission vehicles (Bureau of Energy Efficiency [BEE], 2020).

India also has an ambitious target of at least 30 per cent new electric vehicle sales by 2030, under the EV30@30 initiative, a global campaign promoting EV adoption (Clean Energy Ministerial, 2025).

These policies collectively shape the environment within which the BAU and Ambitious scenarios have been developed.

Results

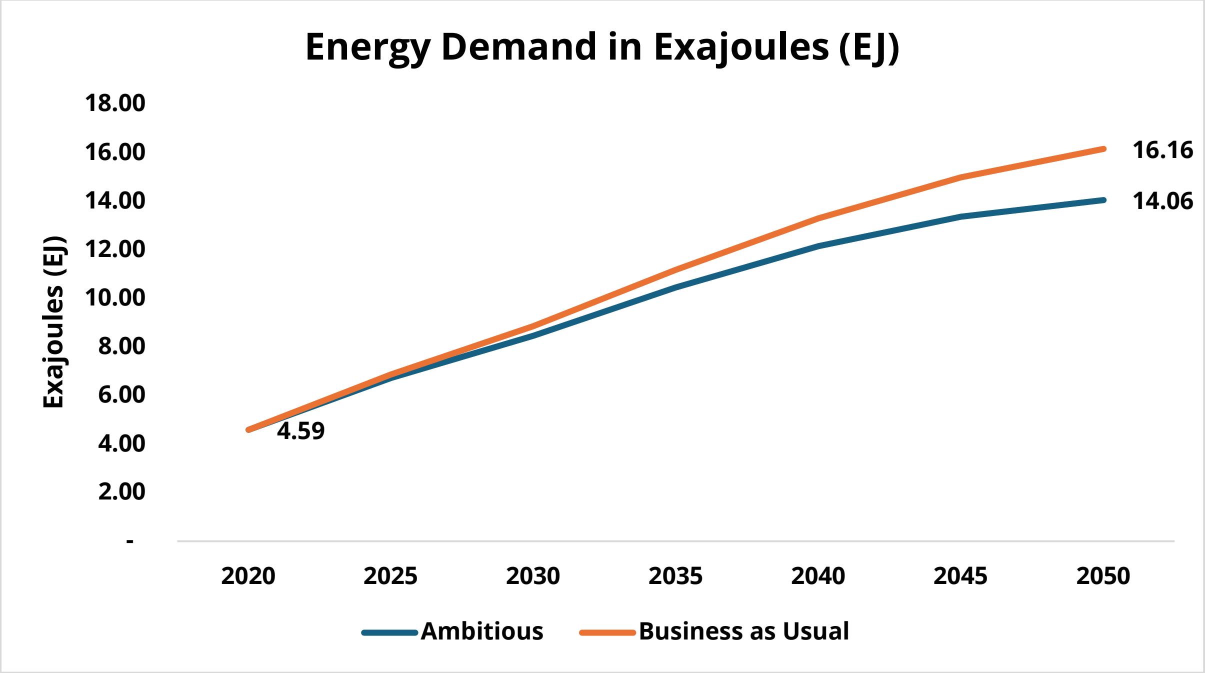


Figure 3: Transport Sector Energy Demand Projections

Figure 3 presents projected total energy demand from India's transport sector under the Business-as-Usual (BAU) and Ambitious scenarios for 2020-2050.

Under the BAU pathway, energy demand rises from 4.59 EJ in 2020 to 16.16 EJ in 2050, corresponding to a compound annual growth rate (CAGR) of approximately 4.3%. This growth reflects sustained expansion in passenger and freight activity, driven by economic development, population growth, and continued reliance on fossil fuels. The Ambitious pathway, which assumes accelerated uptake of cleaner fuels and moderate modal shifts toward public and shared transport, results in a comparatively lower energy demand of **14.06 EJ in 2050**, around **13 per cent lower** than BAU levels. Here, modal shifts refer to an increasing share of public and shared transport modes, such as rail and buses, in overall transport activity, as detailed in the scenario assumptions provided in the Appendix.

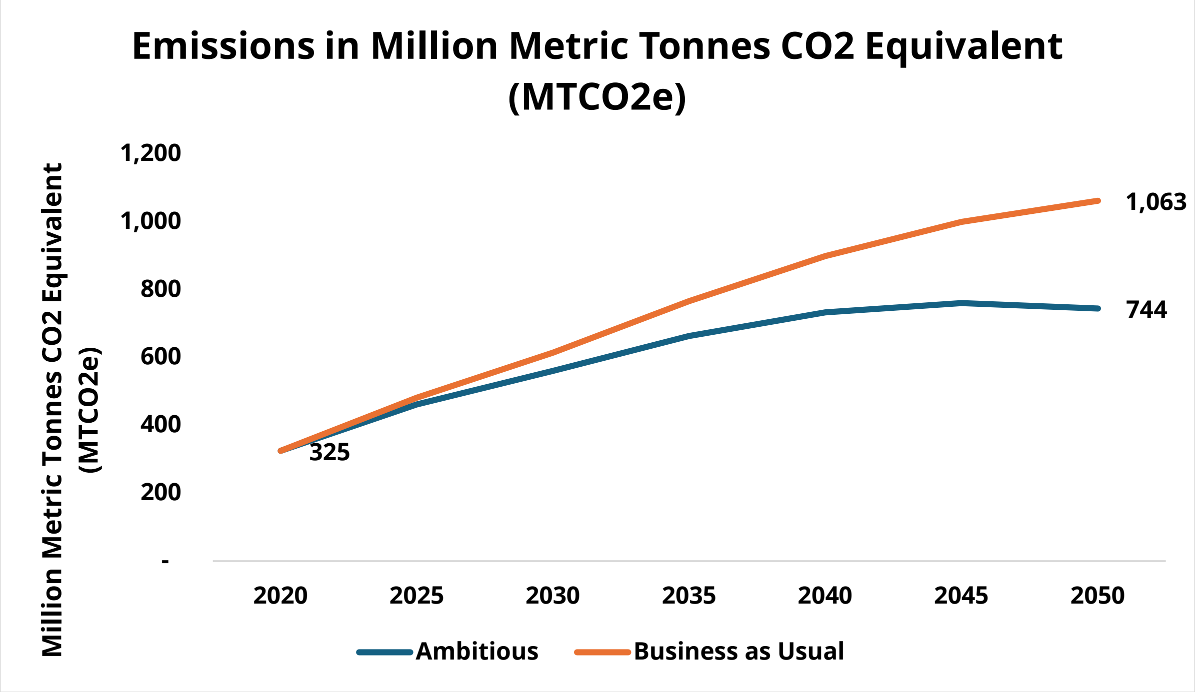


Figure 4: Transport Sector CO2 Emissions Projections

Figure 4 shows total greenhouse gas emissions from the transport sector over the same period. Under the BAU scenario, emissions rise steeply from **325 million tonnes CO_2e in 2020** to **1,063 million tonnes CO_2e in 2050**, driven by the dominance of petroleum-based fuels and the growing stock of internal-combustion vehicles.

In the BAU scenario, the scale of projected emissions could exacerbate existing environmental challenges such as poor air quality and climate change.

This will lead to poor public health and economic losses. Figure 4 shows that emissions under the Ambitious scenario increase more slowly, peaking around the mid-2040s and reaching **744 million tonnes CO_2e by 2050**, approximately **30 per cent lower** than in the BAU case.

The difference between the two scenarios becomes more visible as we move towards 2050, as differences in the level of ambition across key scenario assumptions for 2050, such as fuel mix, efficiency improvements, and modal shares, lead to increasingly divergent outcomes over time. While energy demand continues to grow in both cases due to higher income levels, population growth, and expanding freight needs, the Ambitious scenario shows that ambitious and aggressive policy action can make a big difference. Measures such as improving fuel efficiency, shifting more people to public and shared transport, and introducing cleaner fuels in the mix, together slow down the overall growth in energy demand. This shows that the trajectory of India's transport energy demand and the sector's emissions will depend on how effectively efficiency improvements, cleaner fuels, and modal shifts are scaled up over the next two and a half decades.

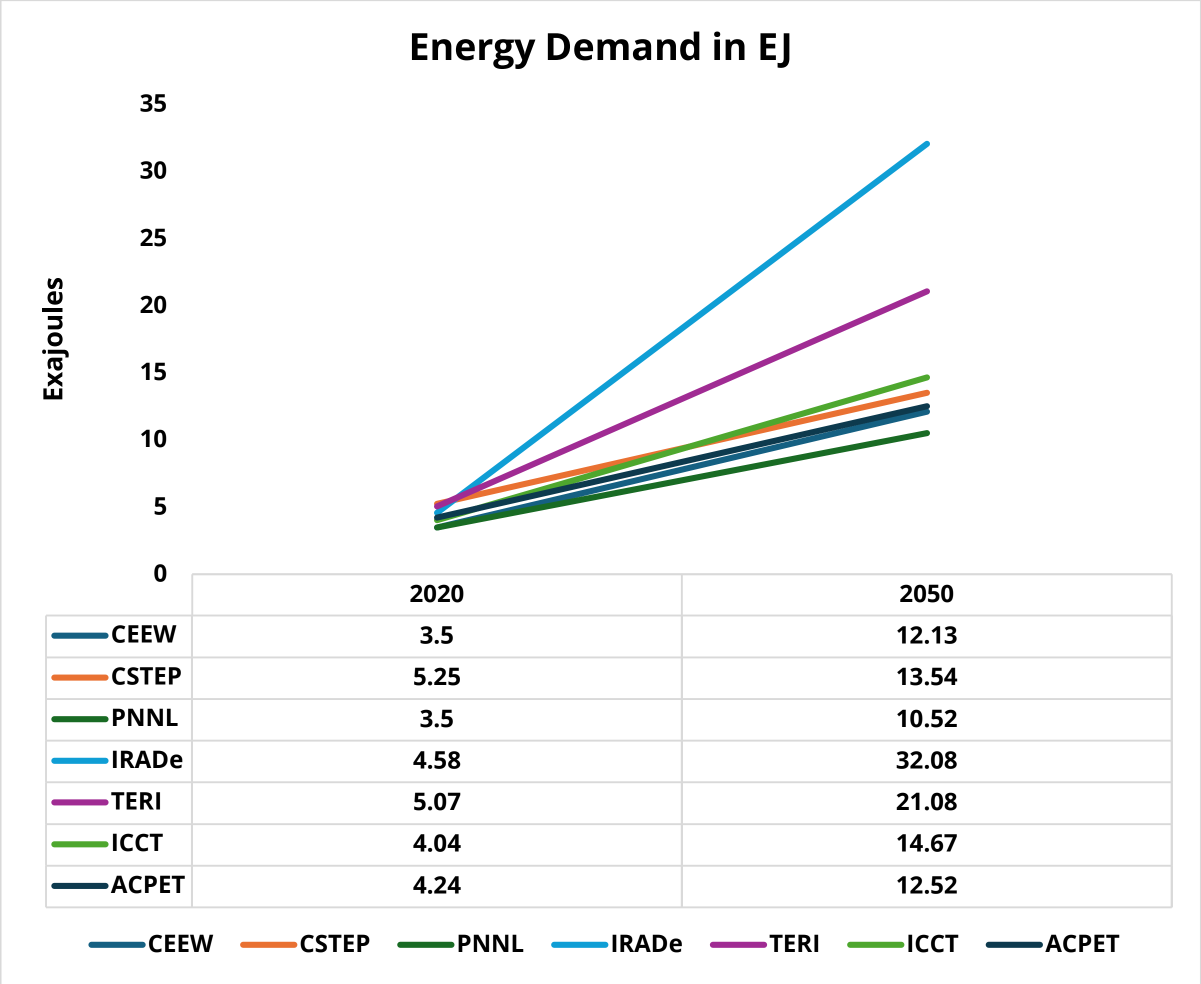
A similar pattern is seen for emissions. In the BAU case, emissions continue to increase sharply through 2050, indicating that without major policy and technological shifts, the sector remains dependent on conventional fuels for transportation. The continued use of diesel and petrol vehicles accounts for most of this rise. It reflects strong path dependency, as the existing vehicle fleet and fuel infrastructure continue to lock the sector into fossil-fuel use. In contrast, the Ambitious scenario reflects the combined impact of more electric vehicles and efficiency improvements, especially visible after 2040. The curve begins to flatten slightly after the mid-2040s, suggesting the sector could see a decline in emissions if these efforts are maintained.

The success of the interventions assumed in the Ambitious scenario depends on several enabling factors, including the availability of cleaner electricity (from non-fossil sources), adequate charging and refuelling infrastructure, development of well-planned cities that reduce the need for private travel, and behavioural shifts towards active and non-motorised modes of transport. These aspects are not explicitly modelled in this study, but they are critical for achieving the projected decline in emissions. Lower energy use and reduced emissions generally bring wider benefits, including lower demand for petroleum products. Reduced oil consumption can make India's energy supply more secure and less dependent on imports. Lower vehicle pollution could improve urban air quality and reduce health risks, especially in congested cities. This highlights that cleaner transport is not just about climate goals; it is equally about better health, cleaner air, and economic resilience.

Overall, the analysis shows that achieving a low-emission transport future will require ambitious and sustained policy action. The 13% lower energy demand and nearly 30% lower emissions seen in the Ambitious scenario, as compared to the BAU scenario, are a direct result of deliberate policy measures modelled as key interventions and levers. The results point to light commercial vehicles (LCVs) as the largest contributors to both energy use and emissions by 2050, highlighting the importance of targeted electrification and efficiency improvements in this segment**.** Maintaining this progress will require consistent implementation, stronger coordination between ministries, and long-term commitment to electrification, public transport, and clean fuels.

Model Results Validation

To situate the ACPET Transport Model within published studies on India's transport sector modelling, a visual cross-comparison has been carried out using results from two widely referenced sources: *India's Electric Vehicle Transition: Post-COVID-19 Economic Recovery Pathways* published by the Council on Energy, Environment and Water (CEEW) in 2020, and *Decarbonizing India's Road Transport: A Meta-Analysis of Road Transport Emissions Models* published by the International Council on Clean Transportation (ICCT) in 2022. Since the CEEW study presents modelling results for road passenger transport only, while the ICCT meta-analysis synthesises outcomes for road passenger and freight transport combined, the figures compare ACPET's road transport energy demand and tailpipe emissions within this scope. These comparisons are presented in Figures 5 (Energy Demand Comparison, 2020–2050), 6 (Energy Demand Comparison, 2030), and 7 (Tailpipe Emissions Comparison, 2020–2050).



	2020	2050
CEEW	3.5	12.13
CSTEP	5.25	13.54
PNNL	3.5	10.52
IRADe	4.58	32.08
TERI	5.07	21.08
ICCT	4.04	14.67
ACPET	4.24	12.52

Figure 5: Energy Demand comparison across models (2020-2050)

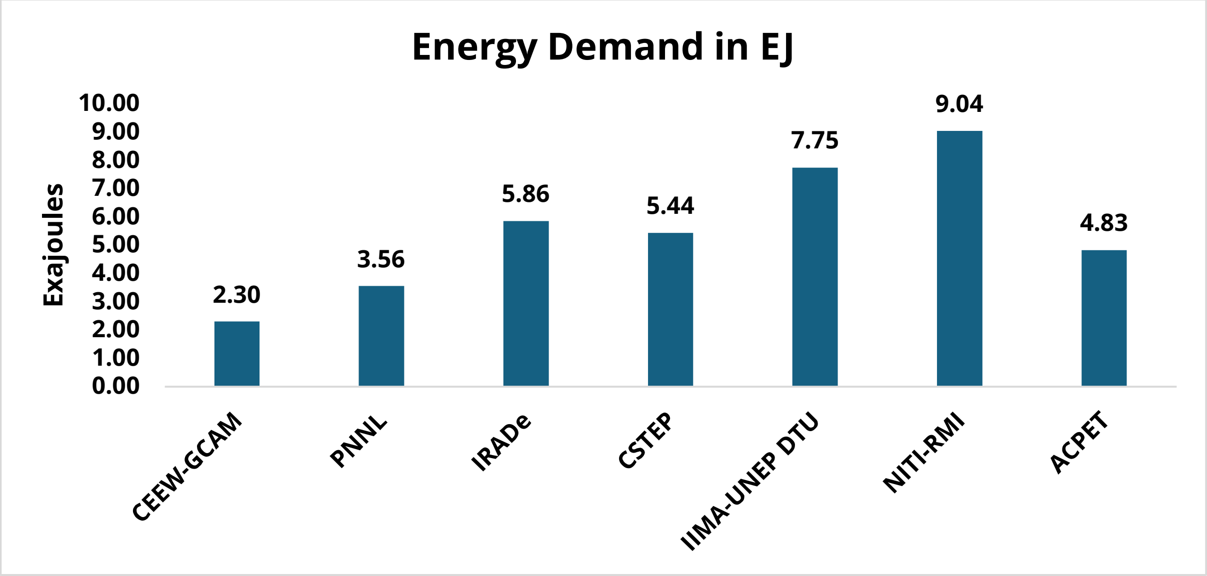
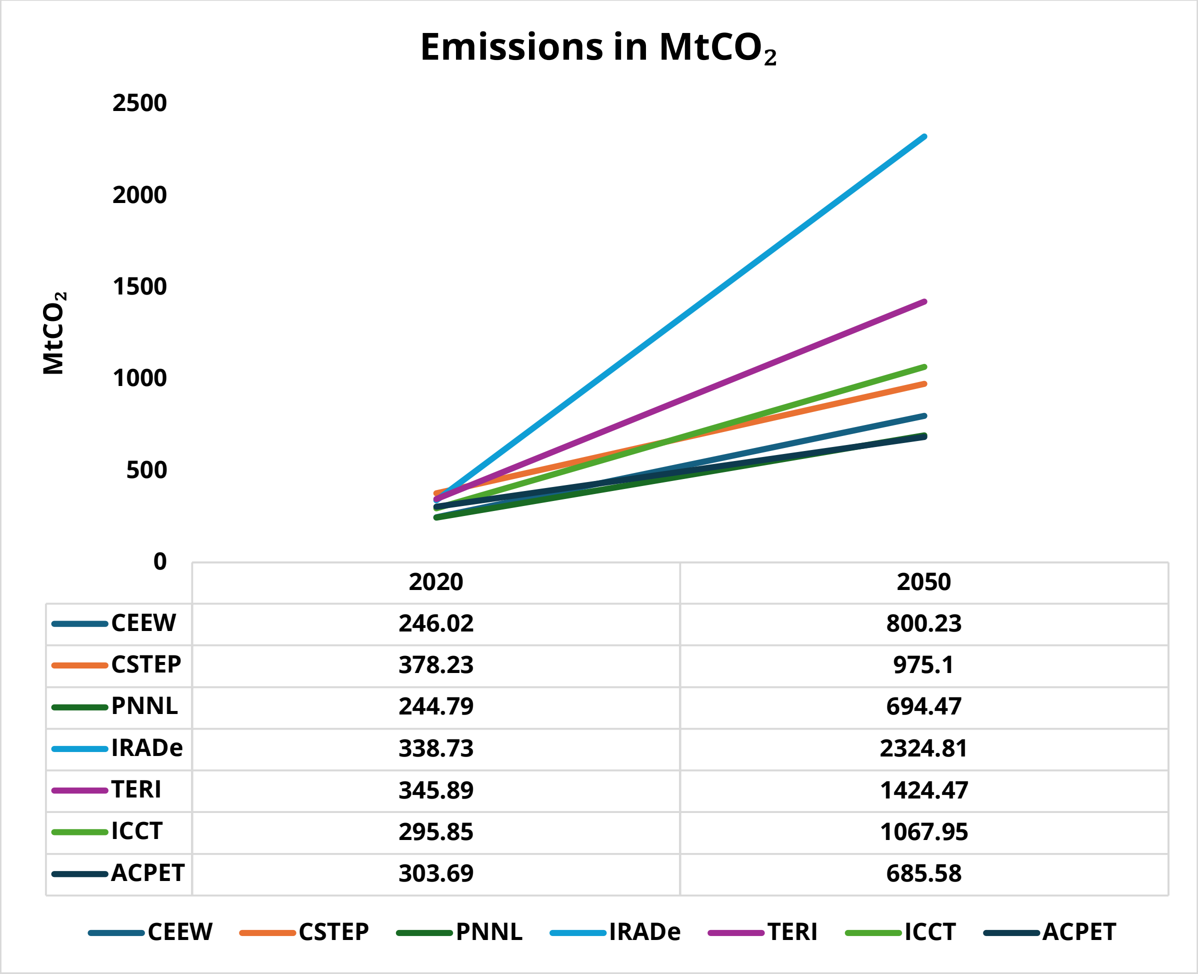


Figure 6: Energy Demand comparison across models (2030)



	2020	2050
CEEW	246.02	800.23
CSTEP	378.23	975.1
PNNL	244.79	694.47
IRADe	338.73	2324.81
TERI	345.89	1424.47
ICCT	295.85	1067.95
ACPET	303.69	685.58

Figure 7: Tailpipe Emissions comparison across models (2020-2050)

The figures present ACPET's modelling estimates alongside published results from CEEW and ICCT for comparable indicators. The values are reproduced as reported in each study and are placed together solely to illustrate the spread of outcomes emerging from different road transport models in India. As presented, the figures offer a literature-based context for interpreting ACPET's results within the range of nationally referenced assessments.

Study Limitations

This study focuses on road, rail, and domestic air transport and does not include metro systems or water transport, which are outside its current scope. The analysis is also not designed to represent a Net Zero 2070 outlook; instead, it explores medium-term pathways up to 2050 to understand the effects of existing and potential policy actions. In addition, biofuels are not yet represented in the model, and their role in future reductions of transport emissions will be incorporated in subsequent updates of the LEAP-ACPET framework. The study also does not assess environmental externality costs or broader socio-economic impacts, which remain outside the scope of the current analysis.

Beyond Technological Pathways

While the scenario-based modelling presented above quantifies the impact of technological transitions such as electrification, cleaner fuels, efficiency improvements, and modal shifts, achieving these outcomes in practice also depends on behavioural changes among consumers and institutions. Recognising this, ACPET undertook a complementary analytical exercise examining the role of behavioural nudges in accelerating the adoption of sustainable mobility solutions. By influencing travel choices, vehicle adoption decisions, and modal preferences, behavioural interventions can reinforce the technological and policy measures assessed in the modelling framework, thereby enabling a more comprehensive and people-centric transition in the transport sector.[1]

Role of Behavioural Nudges in Accelerating Sustainable Mobility

In addition to technology and policy interventions, behavioural science offers powerful tools to accelerate the transition towards sustainable mobility. Behavioural nudges, defined as subtle modifications in the choice environment that influence decision-making without restricting options, can encourage individuals and institutions to adopt cleaner transport solutions. These interventions complement traditional regulatory and financial measures by addressing cognitive and social drivers of behaviour.

Key Areas of Application

- **Electric Vehicles (EVs):** Default procurement of EVs in government fleets, preferential parking, toll exemptions, battery leasing models, and collaboration with ride-hailing services to enhance exposure and reduce adoption barriers.
- **Cleaner Fuels (CNG, Biofuels, Hydrogen):** Framing cleaner fuels as environmentally responsible and nationally beneficial choices, along with visibility and accessibility enhancements.
- **Modal Shift to Public and Shared Transport:** Social norm messaging, real-time information systems, and integrated ticketing to encourage a shift away from private vehicle use.
- **Non-Motorised Transport (NMT):** Urban design cues, safety assurances, and awareness campaigns to promote walking and cycling.

Types of Behavioural Nudges

- **Default Options:** Making sustainable choices the automatic or preferred option.

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[1] Adapted from *Role of Behavioural Nudges in Accelerating the Shift to Sustainable Mobility*, ACPET, authored by Ms Ilika Mohan and Ms Kasvi Sansanwal.

- **Framing and Messaging:** Presenting information in ways that emphasise environmental and social benefits.
- **Social Norms:** Highlighting widespread adoption to encourage similar behaviour.
- **Convenience and Visibility:** Enhancing accessibility and ease of use of sustainable transport modes.

Policy Relevance

Behavioural nudges are typically low-cost, scalable, and capable of delivering rapid impacts when integrated with broader policy frameworks. When combined with technological transitions and infrastructure investments, they can significantly accelerate progress toward India’s Net Zero 2070 and Viksit Bharat 2047 goals, reinforcing a truly people-centric energy transition.

4.2. Industry Sector

Introduction

The industrial sector, which promotes urbanisation, constructs infrastructure, and boosts employment and GDP, is the cornerstone of India's economic expansion. The energy-intensive sub-sectors, such as cement, Aluminium, chlor-alkali (caustic soda and soda ash), iron and steel, and others, enhance India's competitive position in manufacturing, construction, and exports.

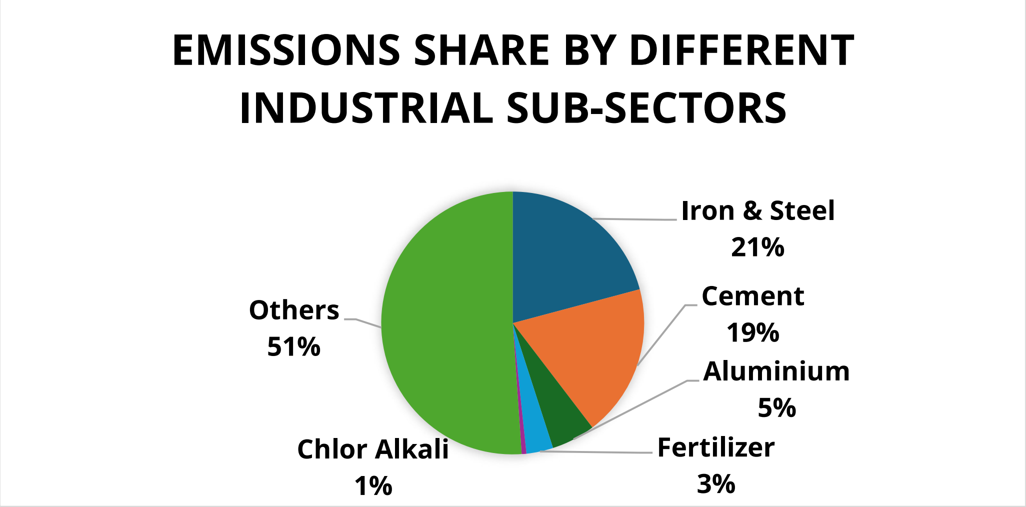

Figure 8: Share Emissions by different sectors in FY 2021-22

Approximately 35% of India's total final energy consumption was derived from the industrial sector, the second-largest energy-consuming sector after the power sector (IEA, 2023). The Industry Sector emitted approximately 803 million metric tonnes of CO2e (MMtCO2e), equivalent to 30 per cent of national emissions in 2019 (MoEFCC, 2023). As India moves towards a low-carbon economy and net-zero emissions by 2070, reducing the energy intensity and carbon footprint of this sector is an essential part of National Climate Action. The industrial sector's energy consumption is projected to increase steadily due to factors such as urbanisation, demographic shifts, and rising output. However, there is also a unique opportunity to transition to low-carbon technologies and fuels and alter the industrial value chain for the long run.

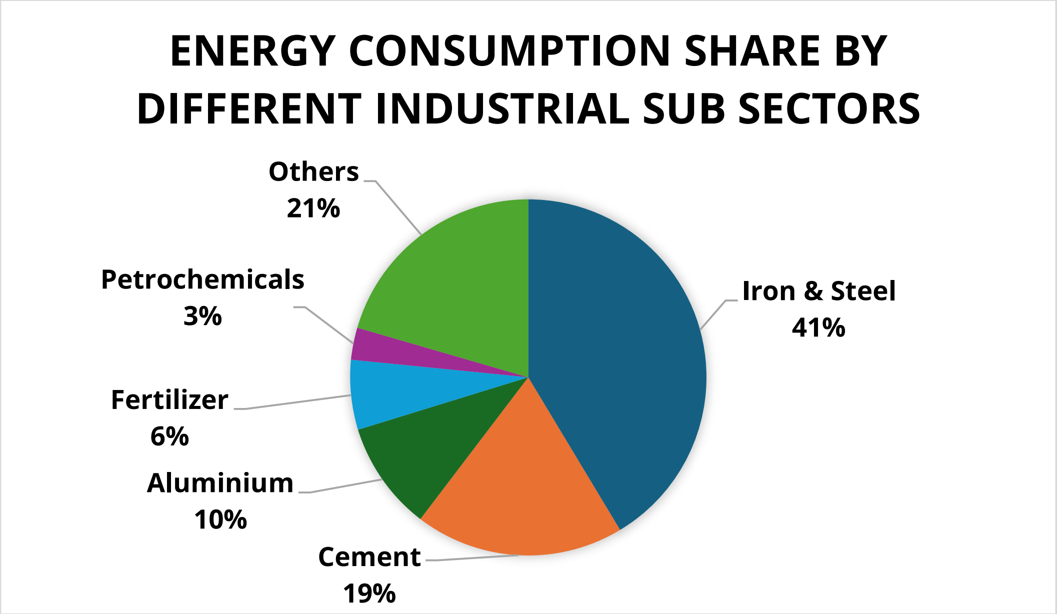

Figure 9: Final Energy Consumption by different sectors in FY 2021-22

In 2019, aggregate emissions from the steel, cement, and chemicals industries totalled 678 MMtCO2e, accounting for almost 68 per cent of the industrial sector's overall emissions (MoEFCC 2023). The increasing demand from infrastructure development, housing, and transportation is projected to more than triple steel output (IBEF 2023) and double cement production (Kumar 2023) by 2050. In a Business-As-Usual scenario that assumes no further low-carbon economy efforts, emissions across the different industrial sectors may rise to 2,657 MMtCO2e by 2050. The increase in emissions renders these industries essential to India's low-carbon economy policy.

Context Setting

India’s industrial sector is entering a decisive phase of transformation. As the backbone of infrastructure development, urban expansion, and manufacturing growth, industry plays a central role in the country’s economic trajectory. At the same time, it represents one of the largest sources of energy consumption and greenhouse gas emissions, accounting for approximately 35 per cent of final energy use and close to 30 per cent of national emissions in recent years [IEA, 2023; MoEFCC, 2023]. Energy-intensive subsectors such as iron and steel, cement, aluminium, and bulk chemicals dominate this footprint.

Material demand is expected to rise rapidly over the coming decades, driven by housing construction, transport infrastructure, electrification, and broader industrialisation. National development strategies envision sustained high economic growth through mid-century, implying substantial expansion in steel, cement, and aluminium production [NITI Aayog, 2023; IBEF, 2023; Kumar, 2023]. Under current production structures, this growth trajectory risks locking the industrial sector into a high-energy and high-emissions pathway, increasing future transition costs and placing additional pressure on energy supply systems.

India's climate commitments, including its updated Nationally Determined Contribution and net-zero target for 2070, require a fundamental shift in how industrial output is produced. Unlike other sectors, industrial emission mitigation involves not only energy substitution but also big changes in production technologies, material efficiency, recycling systems, and infrastructure planning. Process emissions in cement and primary metals, reliance on coal for high-temperature heat, and long-lived capital assets further complicate the transition [IPCC, 2022].

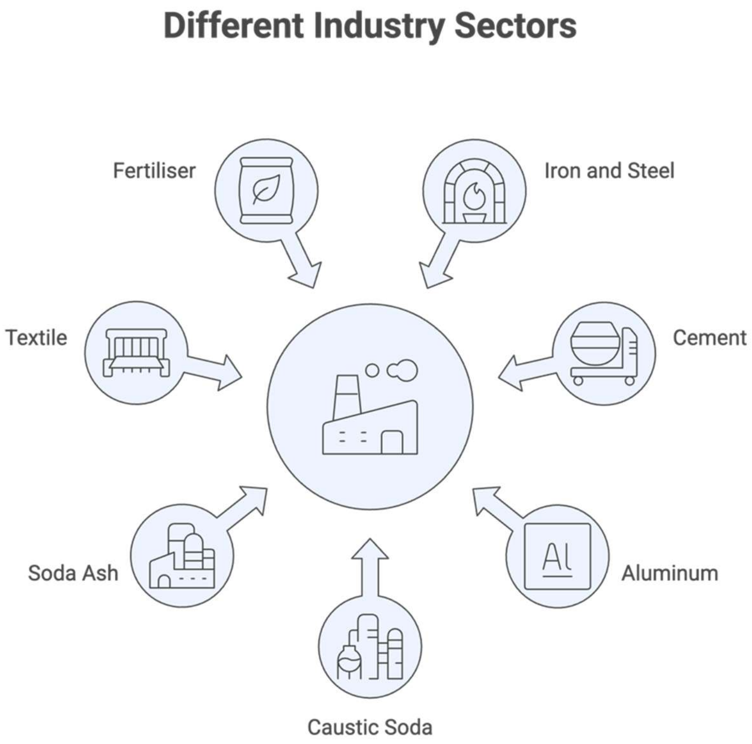

Figure 10: Technologies considered

Recent policy initiatives, including the National Green Hydrogen Mission and the expansion of renewable electricity capacity, signal growing momentum toward industrial emission mitigation. However, the pace and scale of change required extend beyond incremental efficiency improvements. Achieving alignment with long-term climate objectives demands coordinated action across multiple sectors, combining demand-side moderation with structural transformation of supply chains and production routes.

Within this context, there is a need for integrated, sector-spanning assessments that link material demand growth with technology transitions and energy system evolution. This study responds to that need by examining alternative development pathways for key industrial subsectors using a unified modelling framework, with particular attention to energy demand trajectories and the role of circular economy strategies.

Literature Review

Industry accounts for approximately 35 per cent of India's total final energy consumption and nearly 3 per cent of national greenhouse gas emissions, making it the second-largest energy-consuming sector after power [IEA, 2023; MoEFCC, 2023]. In absolute terms, industrial emissions reached roughly 803 $MtCO_2e$ in 2019, with steel, cement, and chemicals contributing close to 68 per cent of this total. Under business-as-usual trajectories, emissions from Indian industry are projected to exceed 2.6 $GtCO_2e$ by 2050, driven primarily by rapid growth in material demand associated with urbanisation and infrastructure expansion.

Global mitigation assessments consistently identify industry as one of the most challenging sectors to decarbonise due to the coexistence of fuel combustion emissions, process emissions, and long-lived capital stock [IPCC, 2022]. Integrated modelling studies show that incremental energy efficiency improvements typically deliver only 10 to 20 per cent reductions in sectoral emissions by mid-century, whereas deep emission mitigation pathways require structural shifts toward electrification, hydrogen, material efficiency, and circular economy strategies [IRENA, 2022; Van Vuuren et al., 2011].

India's iron and steel industry exemplifies this structural challenge. In 2022, crude steel production reached 125.3 million tonnes, making India the second-largest producer globally. However, per capita steel consumption remains low at about 93.5 kg, indicating significant hidden demand [World Steel Association, 2023]. The current output mainly relies on coal-based blast furnaces and basic oxygen furnaces, and on the DRI method, which produces emissions of over 2.5 tCO_2 per tonne of crude steel, above the global average of around 1.9 tCO_2 [IEA, 2020]. Technology roadmaps suggest that hydrogen-based DRI with electric arc furnaces could cut emissions by 85-95% compared to traditional BF-BOF routes. Additionally, scrap-based EAF approaches save 60-65% of final energy per tonne of steel [IEA, 2020; TERI, 2020]. Still, scrap accounts for less than a third of India's steel feedstock due to fragmented collection systems and limited processing infrastructure, even after the implementation of the Steel Scrap Recycling Policy [Ministry of Steel, 2019; Joint Plant Committee, 2023].

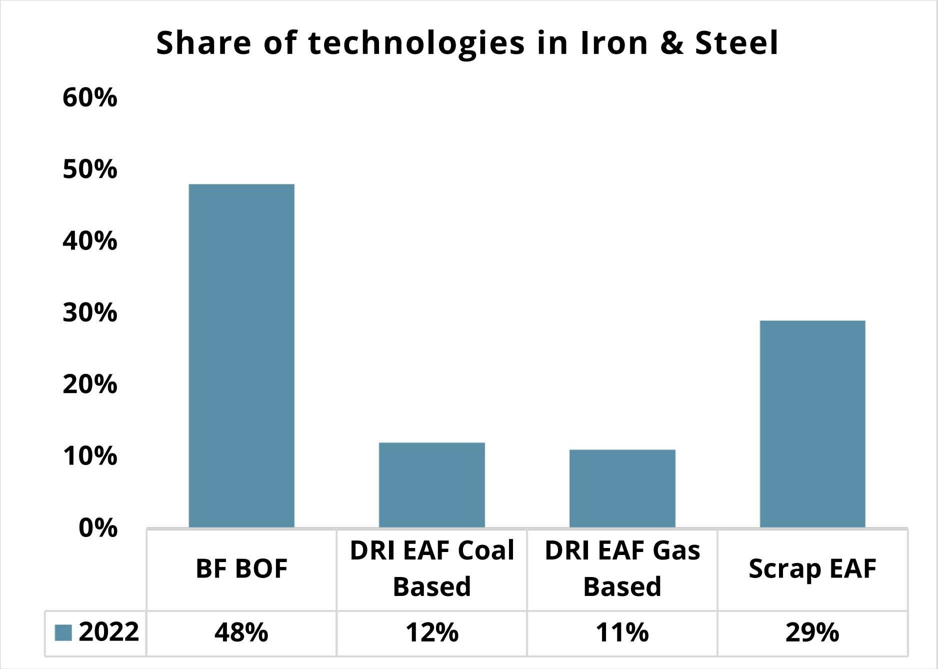

Figure 11: Share of Technologies in Iron and Steel in FY 2021-22

A similar pattern emerges in cement. India produced over 390 million tonnes of cement in 2022, ranking second globally, with production expected to double by 2050 under current development trajectories [CMA, 2022; Kumar, 2023]. Unlike metals, approximately 6 per cent of cement emissions arise from clinker calcination rather than energy use. Although India already achieves blended cement shares exceeding per cent, average clinker factors remain around 0.70, leaving limited scope for marginal improvements [GCCA India, 2023].

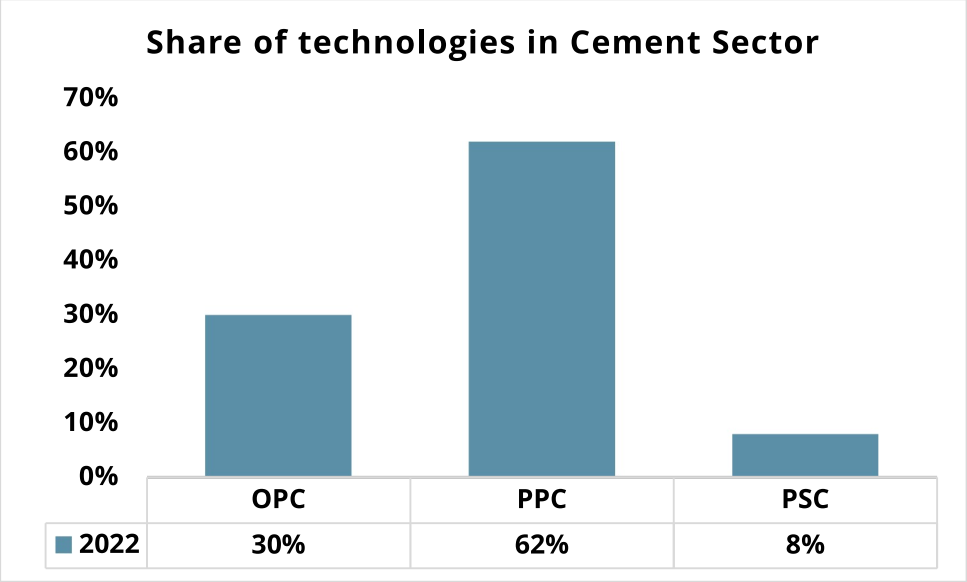

Figure 12: Share of Technologies in Cement Sector in FY 2021-22

Studies by the International Energy Agency and Lawrence Berkeley National Laboratory show that efficiency improvements and alternative fuels can reduce energy intensity by 10 to 15 per cent, but achieving emissions reductions beyond 40 per cent requires aggressive clinker substitution and eventual deployment of carbon capture technologies [IEA, 2018; LBNL, 2020].

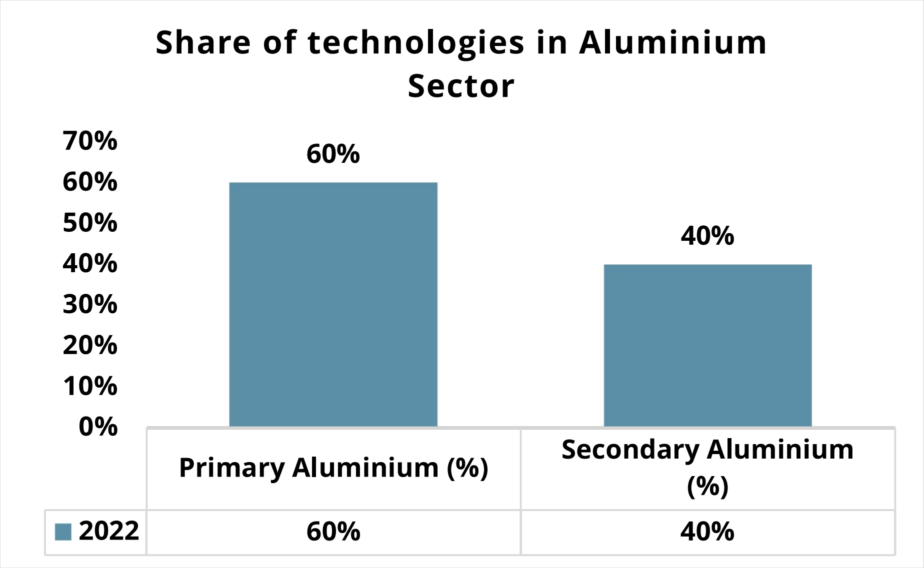

Figure 13: Share of Technologies in the Aluminium Sector in FY 2021.

Aluminium represents one of the most electricity-intensive industrial subsectors. India produced approximately 4 million tonnes of primary aluminium in 2022, with production dominated by the Hall-Héroult process, which typically consumes 13 to 15 MWh of electricity per tonne [IAI, 2022]. Second, aluminium production requires only about 5 per cent of this energy, making recycling the single most effective emission mitigation measure available to the sector [NITI Aayog, 2018; TERI, 2021]. Global pathway studies suggest that increasing recycled content to above 60 per cent, combined with low-carbon electricity, could halve aluminium emissions by mid-century [IAI, 2021]. In India, however, secondary aluminium units account for less than half of total output, reflecting constraints in scrap availability and processing capacity [Ministry of Mines, 2023].

Bulk chemicals add further complexity. India's caustic soda production exceeded 3 million tonnes in 2022, with electricity consumption typically ranging between 2,200 and 2,500 kWh per tonne under membrane cell technology [AMAI, 2021]. The phase-out of mercury cell electrolysis following the Minamata Convention delivered immediate efficiency gains, yet electricity continues to account for over 80 percent of final energy demand in the sector, making emissions trajectories increasingly dependent on grid emission reduction (EP; Department of Chemicals and Petrochemicals, 2023]. Soda ash production, exceeding 3.2 million tonnes annually, remains dominated by the Solvay process, with energy intensities typically above 6 GJ per tonne and heavy reliance on coal and natural gas. Incremental efficiency improvements reduce energy use by only 10 to 20 per cent, while deeper reductions require adoption of modified processes and cleaner energy inputs [Chemical Weekly, 2023; UNIDO, 2020].

Across these subsectors, a consistent quantitative insight emerges that technology and recycling deliver far greater energy and emissions reductions than incremental efficiency measures alone. Circular economy strategies, particularly in metals, are repeatedly identified as among the lowest-cost mitigation options, while hydrogen and electrification become increasingly important beyond 2035 as marginal efficiency gains are exhausted [IRENA, 2022; TERI, 2020].

Recent studies increasingly rely on an integrative framework such as the LEAP, which enables a bottom-up representation of industrial technologies combined with scenario-based policy analysis [Heaps, 2022; SEI, 2022]. Demand-modelling commonly employs income-based functions, such as Gompertz functions, to capture observed nonlinear relationships between income growth and material consumption, thereby providing more realistic long-term projections than linear extrapolation [Van Vuuren et al., 2011].

Despite this growing evidence base, much of the literature remains fragmented across individual subsectors or focused primarily on emissions outcomes. There is limited work that integrates material demand saturation, technology transitions, circular economy strategies, and electrical emission reduction into a single work for India.

Addressing this gap is critical for understanding how alternative development pathways shape long-term industrial energy demand and for identifying policy priorities that can deliver both economic growth and deep emissions reductions.

Rationale

India's industrial sector stands at a critical intersection of economic development and climate responsibility. The sector currently accounts for approximately 35 per cent of total final energy consumption and nearly 330 per cent of national greenhouse gas emissions, with absolute emissions reaching around 803 $MtCO_2e$ in 2019. Energy-intensive subsectors such as iron and steel, cement, aluminium, and glass contribute close to 68 per cent of total industrial emissions. At the same time, material demand is projected to rise sharply, with steel output expected to more than triple and cement production expected to double by mid-century, driven by infrastructure expansion, housing demand, and broader industrialisation. India's industrial sector could escalate to approximately 2,657 $MtCO_2e$ by 2050, placing national climate commitments at significant risk.

While India has articulated ambitious long-term goals, including net-zero emissions by 2070 and enhanced Nationally Determined Contributions, existing policy frameworks and sectoral strategies remain fragmented across individual industries and technologies. Much of the current discourse focuses either on incremental efficiency improvements or on isolated technology pathways, without adequately capturing the combined effects of demand growth, production structure, energy intensity, and circular economy measures. This creates a critical evidence gap for policymakers seeking to design coordinated, system-level interventions.

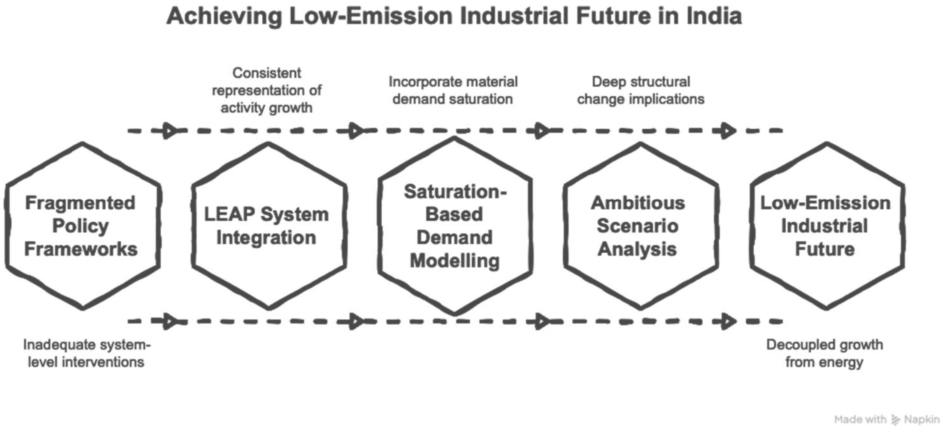

Figure 14: Considered Rationale

Moreover, conventional projections often rely on linear demand growth assumptions, which fail to reflect the observed saturation dynamics of material consumption as economies mature. This limits the ability of existing studies to provide realistic long-term estimates of industrial energy demand and obscures the role of structural transformation in shaping future trajectories. There is a modelling approach to incorporate material demand saturation and side technology transitions.

Against this backdrop, the present study adopts an integrated modelling framework that combines saturation-based modelling, which enables consistent representation of activity growth, technology pathways, and energy intensities across key industrial subsectors, while allowing systematic exploration of alternative futures under varying levels of policy ambition.

By constructing Baseline, Business-As-Usual, and Ambitious scenarios, the analysis moves beyond incremental efficiency narratives to examine the implications of big structural change, including electrification, large-scale deployment, expanded recycling, and circular-economy practices. The Ambitious scenario, in particular, demonstrates the potential to reduce end-use industrial energy demand by more than 60 per cent relative to the Baseline, highlighting the scale of transformation required to decouple industrial growth from energy consumption.

Objectives

India’s industrial sector accounts for approximately 35 per cent of total final energy consumption and nearly 30 per cent of national greenhouse gas emissions, with absolute emissions rising to around 803 $MtCO_2e$ in 2019. Energy-intensive industries like iron and steel, cement, and aluminium dominate the emission footprint and contribute around 68 per cent of the total emissions. At the same time, material demand is projected to rise rapidly as India continues to pursue growth in infrastructure, urbanisation, and manufacturing expansion. Steel production and urbanisation ease at a much faster rate, and the demand for cement is expected to double by mid-century. If the current trend continues without interventions, emissions from the industrial sector could reach around 2,657 $MtCO_2e$ by 2050, creating a substantial gap between India's development trajectory and its long-term commitments.

In this context, the primary objective of this study is to develop an integrated analytical framework to link material demand growth with production technologies and energy use across five industrial sub-sectors. By combining Gompertz-based saturation modelling for steel, cement, and aluminium with the LEAP system, the study aims to move beyond linear projections and provide a realistic assessment of how industrial energy demand may evolve as the economy matures.

A central objective is to examine how alternative development pathways share future trajectories across policy-ambition scenarios. Through the construction of the baseline and the different alternate scenarios, the analysis compares the continued resilience of coal-based production technology routes characterised by gradual efficiency parameters and policy-led structural transformation. For iron and steel, this process involves evaluating transitions from coal-dominated BF, BOF, and DRI routes towards scrap production in EAFs. In the cement sector, the study focuses on shifts from Ordinary Portland Cement (OPC) to Blended Cements like Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC), which, in turn, reduce clinker intensity.

For aluminium, the analysis examines the implications of expanding secondary production beyond its current 40 per cent share, thereby reducing dependence on electricity-intensive primary smelting. In the chemical sector, the study assesses how electricity intensity and energy sourcing influence caustic soda production following the near-complete transition to membrane cell technology, and how efficiency improvements and limited adoption of alternative processes shape energy use in soda ash production.

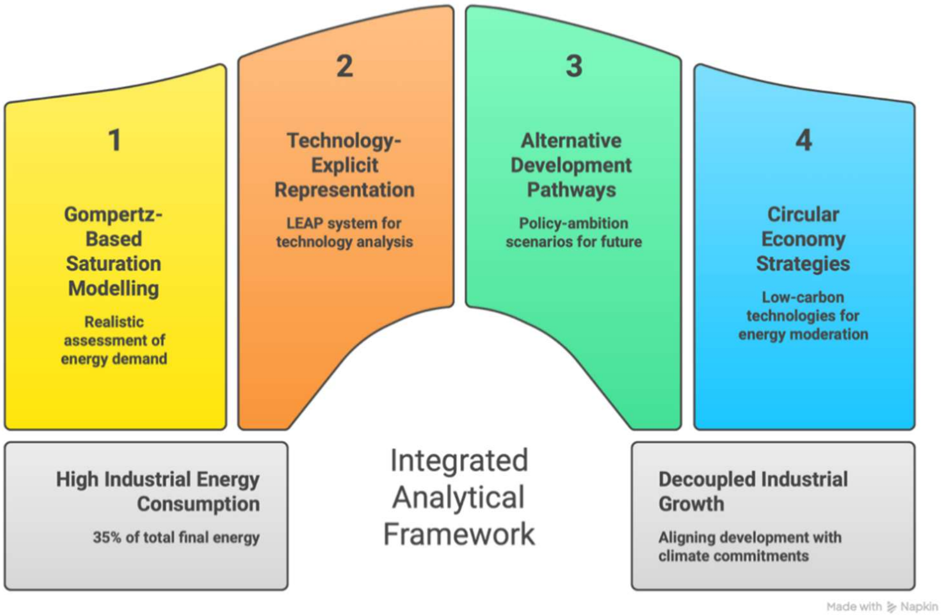

Figure 15: Integrated Analytical Framework used

A central objective is to examine the alternative development path that shapes the future trajectories of the various policy-ambition scenarios. Through the construction of the baseline and the different alternate scenarios, the analysis compares the continued resilience of coal-based production technology routes characterised by gradual efficiency parameters and policy-led structural transformation. For iron and steel, this process involves evaluating transitions from coal-dominated BF, BOF, and DRI routes towards scrap production in EAF. In the thin EAF segment, the study focuses on shifts from Ordinary Portland Cement (OPC) to Blended Cements such as Pozzolana Cement (PPC) and Portland Slag Cement (PSC), which, in turn, reduce cement intensity.

The study also seeks to quantify the role of circular economy strategies and low-carbon technologies in moderating industrial energy demand. Scrap-based steelmaking, which typically requires 60 to 65 per cent less energy than primary routes; secondary aluminium production that bypasses energy-intensive upstream processing; aggressive clinker reduction in cement; electrification of industrial processes; and deployment of green hydrogen are examined as key structural levers. In parallel, the study evaluates how improvements in electricity carbon intensity affect outcomes in highly electricity-dependent subsectors such as aluminium and caustic soda.

Ultimately, the objective is to generate policy-relevant insights that reflect the scale and coordination of interventions required to decouple industrial growth from energy consumption across all five subsectors. By explicitly representing production routes, technology shares, activity growth, and energy intensities within a unified modelling framework, the analysis aims to clarify the limitations of incremental efficiency measures and highlight the conditions under which integrated deployment of recycling, material efficiency, electrification, and low-carbon technologies can align India’s industrial development with its long-term climate commitments while sustaining economic growth.

Research Question

This study is guided by a set of interconnected research questions aimed at understanding how India’s industrial sector can transition toward a low-emission future while sustaining rapid economic growth.

At its core, the study asks how projected growth in material demand across iron and steel, cement, aluminium, caustic soda, and soda ash translates into long-term industrial energy requirements when demand saturation dynamics are explicitly accounted for. By moving beyond linear extrapolation and incorporating Gompertz-based demand modelling, the analysis seeks to clarify how per capita consumption trajectories shape aggregate industrial activity over time.

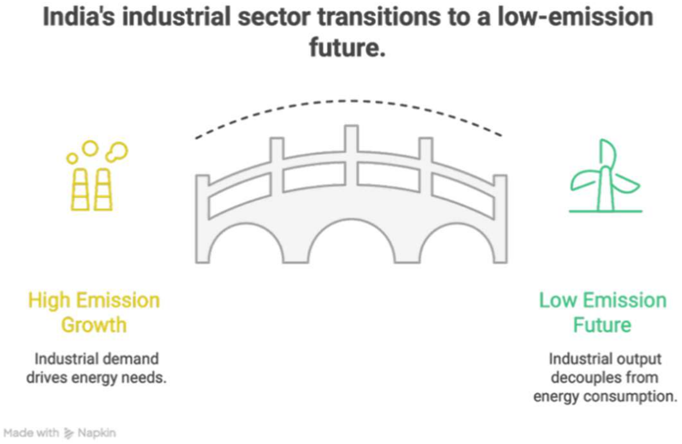

Figure 16: India's Sectoral Transition to a Low Emission Future

Building on this demand perspective, the paper examines how alternative production pathways influence future energy demand under varying levels of policy ambition. It asks how continued reliance on coal-based technologies compares with scenarios characterised by gradual efficiency improvements and policy-led structural transformation, including hydrogen-based steelmaking, expanded recycling in metals, low-clinker cement pathways, electrification of industrial processes, and cleaner electricity supply.

A central research question concerns the role of circular economy strategies in moderating industrial energy growth. The study investigates to what extent increased scrap-based steel production, expansion of secondary aluminium beyond current levels, and greater use of industrial by-products in cement can reduce energy intensity and support decoupling of industrial output from energy consumption.

The paper further explores how electricity-intensive subsectors such as aluminium and caustic soda respond to improvements in electricity efficiency and emission mitigation, and how fuel switching and process optimisation affect energy trajectories in soda ash production. These questions address the extent to which power-sector transitions and industrial technology choices must evolve in parallel to enable large-scale structural change.

Finally, the study asks what combination of policy interventions, technology deployment, and structural shifts is required across all five subsectors to align India's industrial development with its long-term climate commitments. Rather than identifying a single optimal pathway, the research seeks to compare alternative futures and highlight the scale, timing, and coordination of actions necessary to move from incremental efficiency gains toward systemic transformation of the industrial sector.

Methodology

To capture the diversity of production processes, energy use patterns, and emission mitigation pathways across India's industrial landscape, the analysis adopts a subsector-specific modelling approach within a unified LEAP framework. While all subsectors share common macroeconomic and demand assumptions, each is represented by technology-explicit activity trees that reflect sector-specific production routes, material characteristics, and energy-intensity profiles.

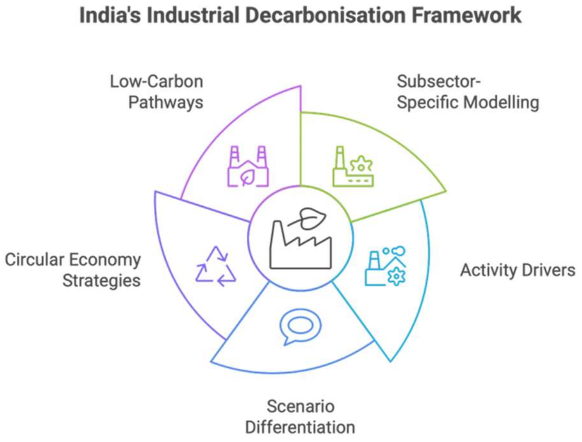

Figure 17: Industrial Emission Mitigation Framework

The modelling framework covers five key industrial subsectors: iron and steel, cement, aluminium, caustic soda, and soda ash. Together, these account for the majority of India's industrial energy consumption and emissions. For each subsector, activity levels are driven either by saturation-based demand projections (steel, cement, aluminium) or exogenously defined production growth trajectories (caustic soda and soda ash). These activity drivers are applied consistently across all scenarios to isolate the effects of technology choice, efficiency improvements, and structural change.

Scenario differentiation is implemented through time-varying technology shares, pathway-specific energy intensities, and fuel substitution assumptions. The Baseline Scenario assumes no additional policy intervention beyond current practices, with technology structures frozen at base-year levels. The Business-As-Usual Scenario incorporates gradual, market-driven efficiency improvements and limited structural shifts. The Ambitious Scenario represents a policy-led transformation characterised by the accelerated deployment of low-carbon technologies, expanded recycling, the electrification of industrial processes, and the integration of green hydrogen.

Circular economy strategies are embedded across relevant subsectors through increased scrap-based steelmaking, expanded secondary aluminium production, and greater utilisation of industrial by-products in cement. Low-carbon production pathways, including hydrogen-based DRI–EAF in steel, low-clinker cement formulations, and electrification of chemical processes, are introduced as distinct technology branches with scenario-specific adoption trajectories.

This consistent modelling structure allows for systematic comparison of alternative development pathways while preserving the technological and operational specificity of each subsector. The following sections describe in detail the methodological treatment of each industrial subsector, beginning with iron and steel, which accounts for the largest share of industrial energy demand and emissions.

Iron and Steel Sector

The iron and steel sector plays a critical role in India's industrial growth and infrastructural development. India is the world's second-largest producer of crude steel, producing 125.3 million tonnes in 2022 (World Steel Report, 2022). Despite this scale in production, the per capita consumption of steel is substantially low for India, i.e., 93.5 kg per person, indicating significant growth potential.

At the same time, the sector is one of the most carbon-intensive in the economy, accounting for more than 30 per cent of the total industrial emissions. The emission intensity exceeds the global average due to a coal-dominated production route, scrap availability and a carbon-intensive electricity mix. Aligning this with India's climate goals requires fundamental shifts and structural changes within the sector.

Technology Pathways Represented in the Model

The modelling framework represents four principal steelmaking routes. The Blast Furnace Basic Oxygen Furnace route remains the most energy- and emission-intensive technology. It currently dominates large-scale production of Direct Reduced Iron (DRI), which, when coupled with Electric Arc Furnaces, is widely used due to the availability of coal. However, it still emits high levels of pollution. Gas-based DRI EAF is less emission-intensive but is constrained by the limited supply of natural gas in India. Scrap-based EAF is the least energy-intensive pathway and is central to circular-economy-driven emission mitigation.

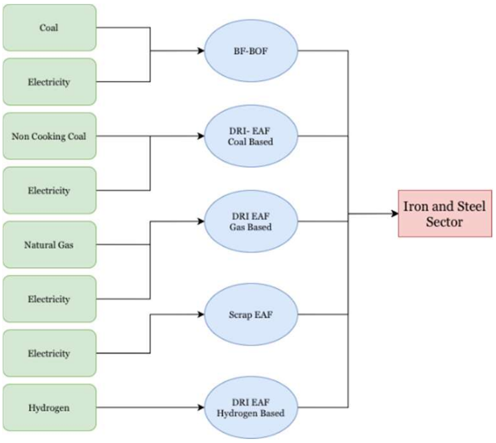

Figure 18: Technologies in Iron and Steel under different scenarios

These technological routes underpin the sectoral activity structure within the LEAP modelling framework.

Scenario Descriptions

Baseline Scenario

The Baseline scenario assumes no additional policy interventions or technological advancements beyond current levels. Technology shares are held constant at their base year values through 2070. Coal-based BF-BOF and DRI routes continue to dominate production, while hydrogen-based steelmaking remains absent. This scenario results in strong fossil-fuel lock-in, rapidly rising energy demand, and emissions trajectories incompatible with long-term climate objectives.

Business-As-Usual Scenario / Current Policy Scenario (CPS)

The Business-As-Usual scenario reflects gradual, market-driven efficiency improvements and compliance with existing energy efficiency regulations. Incremental technological upgrades reduce energy intensity and moderate demand growth, with coal consumption peaking around mid-century. However, structural change remains limited, and the deployment of hydrogen and circular economy pathways occurs only at marginal levels. As a result, emissions reductions are insufficient to meet long-term emission mitigation targets.

Ambitious Scenario

The Ambitious scenario represents a policy-led transformation aligned with India's long-term climate commitments. Strong support for green hydrogen, electrification, scrap recycling, and enabling infrastructure drives a substantial shift away from coal-based production routes. Hydrogen-based DRI-EAF and scrap-based EAF expand significantly by 2047, leading to a sharp reduction in coal use and a more than 50 per cent reduction in final energy demand relative to the Baseline scenario. This pathway achieves a clear decoupling of industrial growth from energy consumption and emissions.

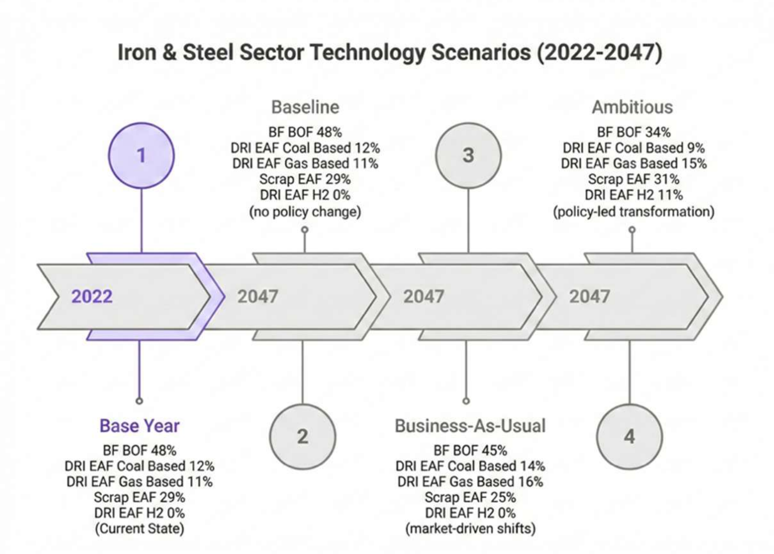

Figure 19: Share of Technologies for Iron and Steel under different scenarios

System Dynamic Modelling for India’s Iron and Steel sector using Stella

Context and Motivation

The broader modelling exercise for this study has used the Low Emission Analysis Platform (LEAP) system to project energy demand, fuel consumption, and Greenhouse Gas (GHG) emissions across India's energy-intensive sectors out to 2047. While LEAP provides robust, scenario-based accounting for energy flows and emissions, it serves only as a system accounting tool. LEAP does not natively capture the feedback loops, nonlinear dimensions, and behavioural interdependencies that characterise complex industrial transitions.

To address this gap, a complementary System Dynamics model has been developed specifically for the Iron and Steel sector using Stella. This sector is prioritised for in-depth SD modelling because of its outsized contribution to industrial emissions, the complexity of its emission mitigation, and the multidimensional feedback between production technology, scrap availability, energy inputs, investment cycles, and policy initiatives.

The Stella model is designed to sit alongside the LEAP model and be informed by the broader model rather than replacing it. Together, they provide a more complete analytical framework. LEAP quantifies energy and emissions across different scenarios, while Stella, on the other hand, unpacks the dynamic mechanisms that drive or constrain the sector’s transition over time.

Key Model Linkages

Key linkages between the two models include:

- Shared scenario structure: The Reference and Low-Carbon scenarios defined in LEAP provide the boundary conditions and directional assumptions (e.g., no new BF-BOF plants post-2025, green hydrogen availability post-2040) that are mirrored in the Stella model.
- Aligned production projections: Production levels from regression-calibrated for the manufacturing sector serve as regression anchors for the Stella model's production stock-and-flow structure.
- Consistent emission factors and fuel shares: Fuel mix assumptions and net calorific values used to calculate fuel demand and emissions in LEAP are carried through to the Stella model to ensure comparability of results.
- Cross-validation: Emission and energy outputs from Stella are benchmarked against LEAP outputs to identify divergences attributable to dynamic feedback, providing insight into where linear accounting models may under- or over-estimate transition trajectories.

Why System Dynamics for the Iron & Steel Sector?

The Iron and Steel sector presents a particularly suitable case for System Dynamics modelling due to several structural characteristics:

Long Asset Lifetimes and Capital Lock-in

Blast Furnace–Basic Oxygen Furnace (BF-BOF) plants have operational lifetimes of 25–40 years and represent significant capital commitments. Decisions to invest, retire, or retrofit these assets are driven by complex interactions between current capacity utilisation, projected demand growth, carbon pricing signals, and availability of alternative technologies. These are inherently stock-and-flow dynamics that SD captures well.

Scrap Availability Feedback Loop

Increasing the share of Electric Arc Furnace (EAF) production, a central lever in the low-carbon scenario, is constrained by scrap steel availability, which itself depends on historical production volumes (the 'scrap generation lag'), collection infrastructure, and international scrap trade. As domestic production accumulates over decades, scrap availability grows but with a delay. This feedback between production history and future input material availability is a classic system dynamics structure.

Technology Transition Dynamics

The shift from BF-BOF to EAF, and subsequently to hydrogen-based Direct Reduced Iron (H-DRI) + EAF, involves adoption dynamics governed by relative costs, infrastructure readiness, policy mandates, and industry inertia. SD can model the S-curve diffusion of new production technologies and the co-evolution of green hydrogen supply and steel sector demand.

Investment and Financing Cycles

Emission mitigation investment is not a one-time event but an ongoing flow that responds to policy signals, carbon prices, technology costs, and profitability. The Stella model captures the reinforcing and balancing loops that govern how capital flows into efficient and low-carbon production capacity over time.

Modelling Methodology

Base Methodology (Consistent with LEAP)

The foundational methodology shared between the LEAP and Stella models is described below. Historical production data for the Iron and Steel sector were sourced from:

- The Perform, Achieve and Trade (PAT) scheme of the Bureau of Energy Efficiency (BEE)
- Indian Minerals Yearbooks (IMY) published by the Indian Bureau of Mines
- Annual Survey of Industries (ASI) from the Ministry of Statistics and Programme Implementation (MoSPI)

A regression analysis was conducted between historical production volumes and the Gross Value Added (GVA) of the manufacturing sector to establish a relationship between the two. This relationship was used to project annual production levels through to 2050 (in metric tonnes).

Total energy demand was then estimated by combining projected production with sector-specific energy intensity:

Total Energy Demand (TWh) = Specific Energy Consumption (TWh/T) × Total Production (T)

Specific Energy Consumption (SEC) values were obtained from PAT notifications and company annual reports. The energy demand is disaggregated across fuel types: coal, petroleum coke, natural gas, furnace oil, captive and grid electricity, and alternative fuels (biomass, waste), based on fuel share data from company reports and Central Electricity Authority (CEA) publications.

Total fuel requirements and resulting GHG emissions are calculated as:

Total Fuel Demand = Total Energy Demand (in EJ) × Fuel Share × Net Calorific Value (in MT/TWh)

Total Emissions MTCO2eq = Total Fuel Demand × Emission Factor

<u>Causal Loop Structure in Stella</u>

The Stella model translates the above methodology into a causal loop and stock-and-flow architecture. The core causal structure, as illustrated in the model's causal loop diagram, captures the following feedback relationships:

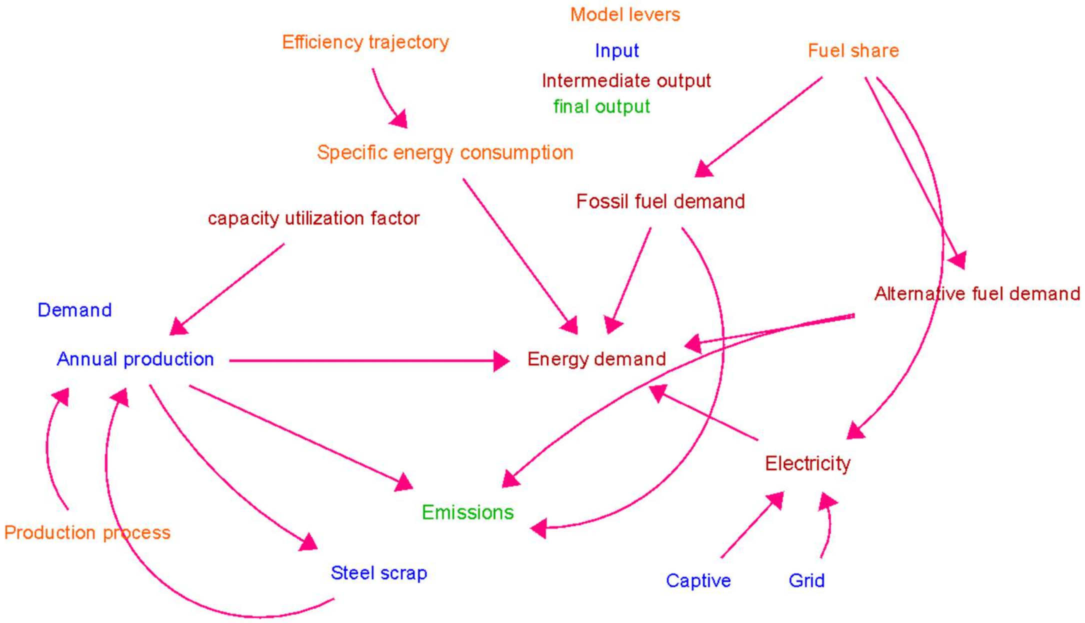

Figure 20: Casual Loop Diagram for the Iron and Steel Sector

Emission Mitigation Levers Modelled in Stella

The low-carbon scenario in Stella operationalises the following transition levers, consistent with the LEAP scenario assumptions:

- No new BF-BOF capacity: From 2025 onwards, no new BF-BOF plants will be commissioned. Existing capacity retires on schedule, with no stranded asset assumptions required due to the fleet's age profile.
- Higher scrap utilisation: Scrap availability increases with asorical production stocks. Higher scrap shares in both BOF and EAF processes reduce iron ore inputs, process energy use, and associated emissions.
- Energy efficiency to BAT levels: All production processes are assumed to reach Best Available Technology (BAT) efficiency levels by 2030, reducing SEC across the board.
- Alternative reducing agents: Hydrogen and biochar are introduced as progressive substitutes for coke in BF-BOF processes, reducing process emissions from the reduction stage.
- Green electricity transition: Increased reliance on grid electricity enabled by Green Energy Open Access, combined with accelerating grid emission mitigation, supports lower-emission steel production.
- Hydrogen-based EAF (post-2040): From 2040 onwards, cost-competitive green hydrogen enables a progressive shift to H-DRI + EAF routes, reaching approximately 60% of total production under the net-zero scenario by 2070.
- Carbon Capture and Storage (CCS): CCS is deployed as a last-mile solution in remaining BF-BOF plants from 2040 onward to address residual hard-to-abate process emissions.

Investment Estimation

The Stella model estimates the investment required to achieve the low-carbon transition by tracking the gap between existing efficient production capacity and the maximum achievable capacity under the assumed CUF:

Gap in Efficient Production = (Efficient Production ÷ Max CUF) - Efficient Capacity Available

Annual Cost for Efficient Production = Marginal Extra Capex × Annual Capacity Addition

This investment flow is modelled as a dynamic variable in Stella responsive to the rate of capacity retirement, production growth requirements, and the cost trajectory of emerging technologies (particularly green hydrogen and EAF infrastructure).

Scenarios

Two scenarios are modelled in Stella for the Iron and Steel sector, mirroring the scenario structure of the broader LEAP analysis:

Reference Scenario

Steel production continues to rely heavily on coal-based BF-BOF technology. Scrap usage and EAF adoption remain limited. Energy efficiency improvements occur, but at a pace consistent with business-as-usual policy implementation. The sector remains a major contributor to industrial GHG emissions, with no significant structural technology shift occurring by 2050.

Low-Carbon Scenario

No new BF-BOF plants are commissioned. The industry progressively transitions to EAF-based production initially powered by grid electricity and later by green hydrogen (post-2040). Scrap utilisation increases in line with growing domestic scrap availability. Energy efficiency converges to BAT levels by 2030. Alternative reducing agents and CCS are deployed in the latter half of the period. The Stella model traces the dynamic trajectory of this transition, capturing delays, tipping points, and the role of reinforcing feedback loops (e.g., declining hydrogen costs enabling accelerating adoption).

Model Outputs and Analytical Value

The Stella SD model generates the following key outputs for the Iron and Steel sector:

- Annual production volumes by technology route (BF-BOF, EAF-grid, H-DRI+EAF)
- Installed and efficient production capacity trajectories
- Annual scrap availability and utilisation rates
- Specific energy consumption evolution by process
- Total energy demand disaggregated by fuel type (coal, gas, electricity, hydrogen, alternative fuels)
- GHG emissions ($MtCO_2eq$) by scope and fuel source
- Annual investment requirements for capacity addition and efficiency upgrades
- Cumulative emissions and investment through 2050 under each scenario

Beyond replicating the LEAP outputs for the steel sector, the Stella model provides additional analytical value by:

- Identifying tipping points and threshold effects in the technology transition (e.g., the year at which EAF becomes cost-competitive without subsidy support)
- Quantifying the delay between policy intervention and emissions reduction, reflecting asset retirement schedules and investment lead times
- Testing the sensitivity of transition pathways to key uncertain parameters, including scrap availability growth rates, green hydrogen cost trajectories, and carbon price levels
- Revealing whether the low-carbon transition is self-reinforcing (driven by positive feedback loops) or requires sustained external policy pressure to maintain momentum

Cement Sector

The cement sector is a critical component of India’s industrial activity and infrastructural development. Demand for cement is closely linked to housing construction, transport infrastructure, urban expansion, and public investment, making the sector one of the drivers of economic growth in the country. At the same time, cement production is among the most energy- and emission-intensive sectors. A defining characteristic of this sector is that a substantial portion of its emissions comes from the chemical process of clinker production rather than solely from use. As the demand for cement is projected to rise sharply in the near future, understanding how energy technology choices and policy interventions influence energy demand trajectories is a pivot to aligning sectoral growth with long-term low-carbon objectives.

Technology Pathways Represented in the Model

The cement sector is represented in the LEAP modelling framework through three dominant cement production pathways, differentiated by clinker content and associated energy intensity.

Ordinary Portland Cement (OPC) is the most clinker-intensive cement type and exhibits the highest energy and emissions intensity. Its production relies heavily on coal for thermal energy, resulting in the highest final energy demand per tonne of cement.

Portland Pozzolana Cement (PPC) partially substitutes clinker with pozzolanic materials such as fly ash. This reduces clinker requirements and lowers both energy consumption and emissions intensity relative to OPC.

Portland Slag Cement (PSC) blends clinker with granulated blast furnace slag and represents the lowest-energy-intensity pathway among the three cement types. Due to its low clinker content, PSC has the greatest potential for reducing energy demand and emissions at the sector level.

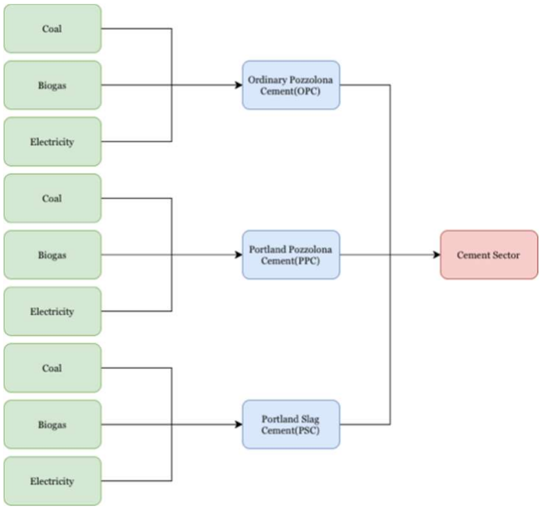

Figure 21: Technologies considered in the Cement Sector

These three cement types form the activity structure in LEAP and determine final energy demand through their distinct clinker factors and fuel requirements. India already exhibits a relatively high share of blended cements, providing a strong structural base for further emission reduction, while also implying that future reductions depend on deeper shifts toward low-clinker products rather than marginal efficiency gains.

Scenario Descriptions

Three scenarios are used to evaluate alternative development pathways for the cement sector.

The Baseline Scenario assumes no additional policy interventions or structural changes beyond existing practices. The production mix remains largely unchanged over time, with OPC retaining a significant share, PPC remaining dominant, and PSC experiencing limited expansion. Coal continues to dominate thermal energy use across all cement types. In this scenario, energy demand increases almost in proportion to cement output.

The Business-As-Usual Scenario reflects gradual, market-driven shifts in production structure and incremental efficiency improvements. The share of OPC declines steadily, while PSC expands moderately. PPC continues to account for a large share of production. These changes reduce the average clinker factor and moderate energy demand growth relative to the Baseline Scenario, but do not fundamentally alter the sector's dependence on clinker-based production.

The Ambitious Scenario represents a policy-led transformation aligned with long-term climate objectives. Blended cements dominate production, OPC is aggressively phased down, and PSC penetration increases substantially. In parallel, alternative fuels expand, and preparations for large-scale deployment of carbon capture technologies are introduced. This scenario delivers the strongest reduction in energy intensity and constrains long-term energy demand growth despite continued expansion in cement production.

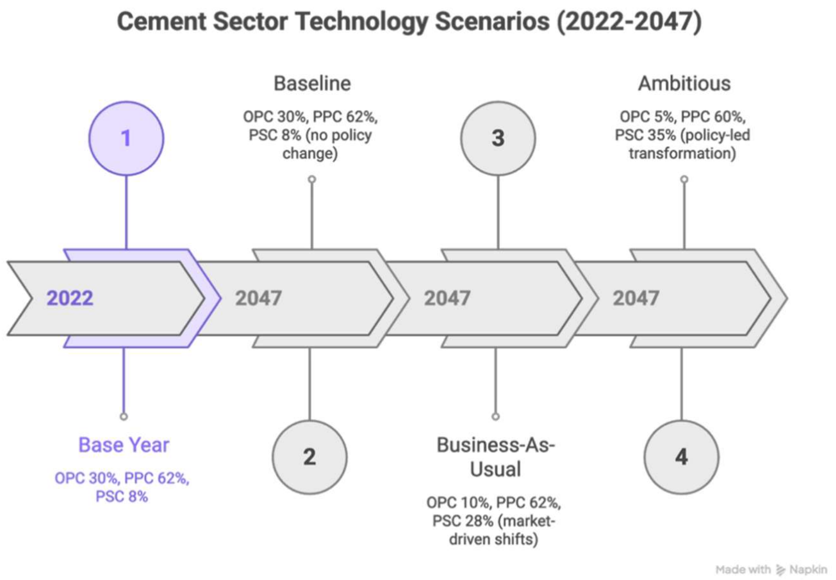

Figure 22: Cement Sector Technology Scenarios

Aluminium Sector

The aluminium sector occupies a strategically important position in India's industrial landscape, supplying essential inputs to construction, transport, packaging, electrical equipment, and the rapidly expanding renewable energy sector. As one of the most electricity-intensive industrial activities, aluminium production plays a disproportionate role in shaping industrial energy demand and emissions trajectories. India is among the world's largest producers of aluminium, with growth driven primarily by primary smelting through the Hall-Héroult process. While technologically mature, this production route is highly energy-intensive and closely tied to the carbon intensity of the electricity grid.

A defining structural challenge for the Indian aluminium industry is the relatively low share of secondary aluminium production. Recycling offers one of the strongest emission reduction levers available to the sector, as secondary aluminium requires only a fraction of the energy needed for primary smelting. This section examines how different levels of policy ambition and technological adoption influence long-term energy demand outcomes for the aluminium sector.

Technology Pathways Represented in the Model

The aluminium sector is represented in the LEAP modelling framework through two principal production pathways with sharply contrasting energy profiles.

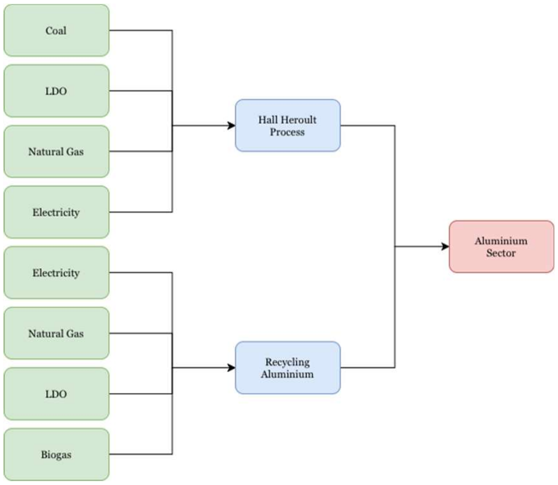

Figure 23: Technologies Considered in the Aluminium Sector

Primary aluminium production is modelled through the Hall-Héroult electrolytic smelting process. This pathway is highly electricity-intensive and relies on carbon anodes, making it among the most energy- and emissions-intensive industrial technologies. Final energy demand under this route is dominated by electricity consumption, and the power system's carbon intensity strongly influences overall emissions.

Secondary aluminium production involves recycling post-consumer and industrial scrap. This pathway bypasses the energy-intensive stages of bauxite mining, alumina refining, and electrolytic reduction. As a result, secondary aluminium requires substantially lower final energy per tonne of output and serves as the backbone of a circular-economy-based emission mitigation strategy.

Scenario Descriptions

All scenarios share a common demand trajectory derived from the saturation-based demand model, but differ in the evolution of the production mix between primary and secondary aluminium.

In the **base year 2022**, aluminium production is dominated by primary smelting, with secondary aluminium accounting for approximately **40 per cent** of total production and primary production accounting for the remaining **60 per cent**. This production structure forms the starting point for all scenarios.

The **Baseline Scenario** assumes no structural change in production technologies. The share of primary aluminium remains fixed at 60 per cent, while secondary aluminium remains at 40 per cent throughout the projection period. Energy demand, therefore, rises sharply with output growth, reflecting the continued dominance of electricity-intensive primary smelting.

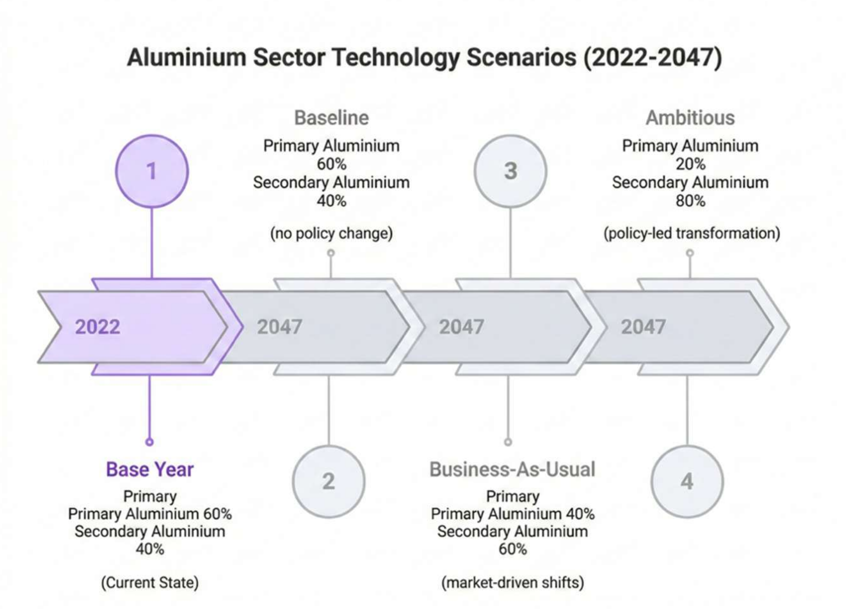

Figure 24: Cement Sector Technology Scenarios

The **Business-As-Usual Scenario** incorporates a gradual market-driven expansion of recycling. Under this pathway, secondary aluminium increases steadily, reaching approximately **60 per cent of total production by 2070**, with primary production declining correspondingly. This shift moderates energy demand growth but does not fundamentally transform the sector's energy profile.

The **Ambitious Scenario** represents a policy-led transformation centred on a circular economy. Recycling expands aggressively, with secondary aluminium reaching **around 80 per cent of total production by 2070**, and primary smelting reduced to a residual share. This scenario assumes strong policy support for scrap collection, processing infrastructure, and enabling regulations.

Results

Iron and Steel Sector

The evolution of final energy demand in the iron and steel sector reveals how policy ambition and technology choices fundamentally shape long-term outcomes. In the base year 2022, final energy demand stands at 3.83 EJ across all scenarios, providing a common reference point for comparison. Beyond this point, the trajectories diverge, reflecting the underlying assumptions embedded in each scenario.

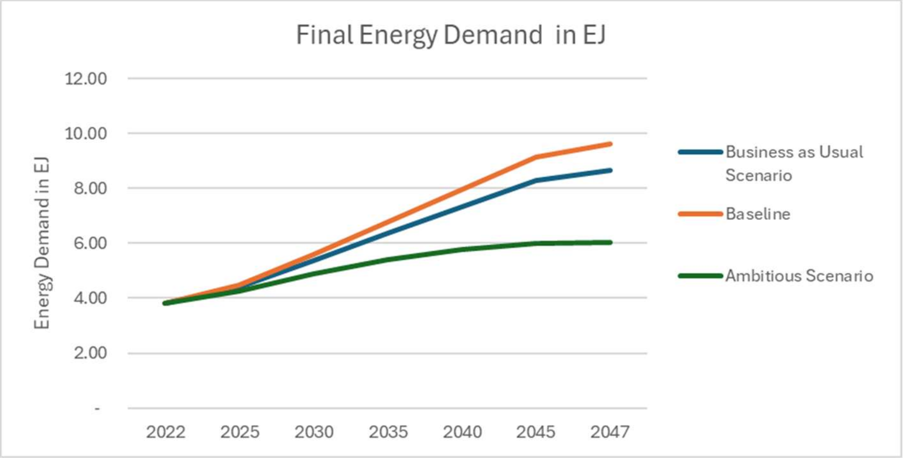

Figure 25: Final Energy Demand for the Iron and Steel Sector

In the **Baseline Scenario**, energy demand increases steadily throughout the projection period, reaching 9.62 EJ by 2047. This more than two-and-a-half-fold increase is driven by continued reliance on coal-intensive production routes and the absence of meaningful technological or structural change. As steel output expands to meet growing demand, energy consumption rises almost in proportion, reinforcing fossil-fuel lock-in and resulting in a high-energy, high-emissions pathway.

The **Business-As-Usual Scenario** moderates this growth to some extent. Final energy demand rises to 8.67 EJ by 2047, remaining below the Baseline but still more than double the 2022 level. Incremental efficiency improvements and gradual process optimisation slow the pace of demand growth, particularly after 2035. However, the underlying production structure remains largely unchanged, limiting the potential for deeper reductions in energy use.

A distinctly different pattern emerges under the **Ambitious Scenario**. Here, final energy demand increases more gradually and stabilises after 2040, reaching 6.03 EJ by 2047. This represents a 37 per cent reduction relative to the Baseline in the same year. The flatter trajectory reflects a structural transformation of the sector, driven by the large-scale adoption of hydrogen-based DRI, expansion of scrap-based EAF production, increased electrification, and improvements in material efficiency. As a result, growth in steel output is increasingly decoupled from energy consumption, aligning the sector with India's long-term low-carbon transition objectives.

Cement Sector

The LEAP results for the cement sector reveal distinct energy demand trajectories across the three scenarios, reflecting the combined effects of production growth, cement composition, and policy intervention.

In the base year 2022, total final energy demand across all scenarios is 0.86 EJ, representing the existing production structure dominated by blended cements but still reliant on clinker-intensive processes and coal-based thermal energy.

Under the Baseline Scenario, final energy demand increases steadily over the projection period, reaching 1.02 EJ in 2030, 1.33 EJ in 2040, and 1.53 EJ by 2047. This represents an increase of nearly 79 per cent between 2022 and 2047. The strong upward trajectory closely tracks cement production growth and reflects the absence of structural change in cement composition. The persistence of Ordinary Portland Cement and the limited expansion of low clinker cement types result in minimal decoupling between output growth and energy demand.

The Business-As-Usual Scenario shows a moderated but still rising energy demand pathway. Final energy demand reaches 1.01 EJ in 2030, 1.29 EJ in 2040, and 1.46 EJ by 2047, remaining consistently below the Baseline Scenario but still increasing by approximately 70 per cent relative to 2022. Incremental shifts toward blended cements and gradual efficiency improvements reduce energy intensity but are insufficient to offset the scale effects of rapid production growth.

The Ambitious Scenario has a great divergence in outcomes. Final energy demand rises more gradually to 0.92 EJ in 2030, 1.04 EJ in 2040, and 1.09 EJ by 2047, representing an increase of only 27 per cent over the projection period. Compared to the Baseline Scenario, the Ambitious pathway reduces final energy demand by approximately 29 per cent in 2047, demonstrating a clear decoupling of cement production from energy consumption through aggressive clinker reduction and structural transformation of the production mix.

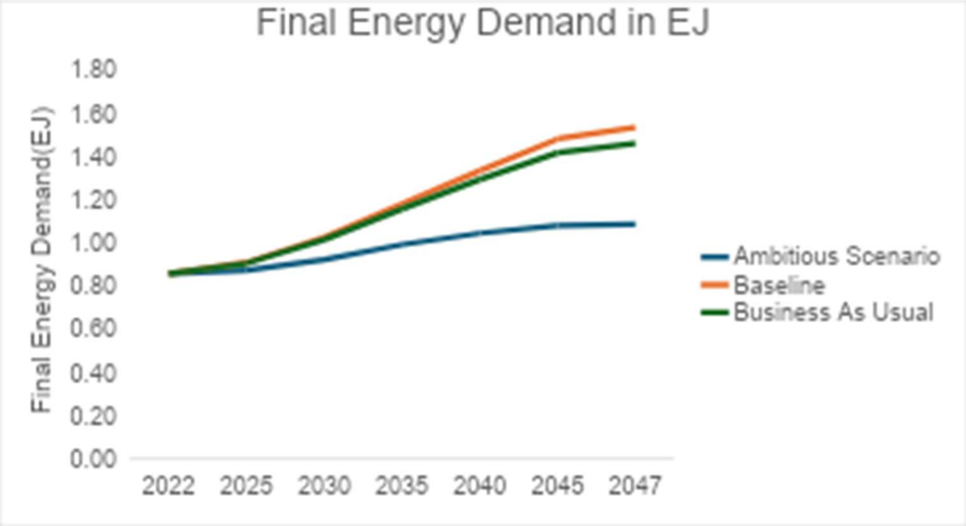

Figure 26: Final Energy Demand for Cement Sector

Across all scenarios, differences in energy demand outcomes are driven primarily by changes in cement type shares rather than by efficiency improvements within individual technologies. Fuel-wise results further show that coal remains the dominant energy source throughout the projection period, accounting for more than 90 per cent of final energy demand even in later years. Biomass and electricity increase in absolute terms but remain secondary contributors, underscoring that fuel substitution alone delivers limited gains without clinker reduction.

Aluminium Sector

LEAP results reveal sharply diverging energy demand trajectories across the three scenarios.

In the base year **2022**, final energy demand in the aluminium sector is **0.87 EJ** across all scenarios. Under the **Baseline Scenario**, final energy demand increases rapidly to **1.44 EJ by 2030**, **2.68 EJ by 2040**, and **3.77 EJ by 2047**. This represents more than a **fourfold increase** over the projection period and reflects the continued dominance of electricity-intensive primary aluminium production.

The **Business-As-Usual Scenario** moderates but does not reverse this trend. Final energy demand reaches **1.45 EJ in 2030**, **2.62 EJ in 2040**, and **3.59 EJ by 2047**. Although increased recycling reduces average energy intensity relative to the Baseline Scenario, absolute energy demand continues to rise sharply due to strong growth in aluminium output.

The **Ambitious Scenario** exhibits the strongest divergence in outcomes. Final energy demand rises to **1.28 EJ by 2030**, **2.03 EJ by 2040**, and **2.54 EJ by 2047**. Compared to the Baseline Scenario, the Ambitious pathway reduces final energy demand by approximately **33 per cent in 2047**, demonstrating a clear decoupling of aluminium production growth from energy consumption through aggressive expansion of secondary aluminium.

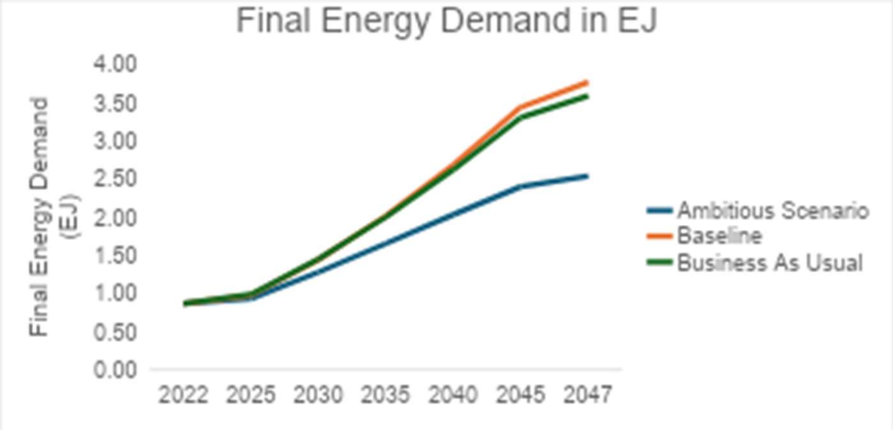

Figure 27: Final Energy Demand for the Aluminium Sector

Across scenarios, the results confirm that **production mix is the dominant driver of energy outcomes**. Efficiency improvements within primary smelting play a limited role, while large-scale substitution toward secondary aluminium delivers substantial reductions in long-term energy demand.

4.3. Agriculture Sector

Introduction

The agriculture sector remains the most critical component of the Indian economy, employing close to 45% of the total workforce and contributing approximately 16-18% of the country's Gross Value Added (GVA). In addition to its economic role, agriculture is also a major consumer of commercial energy, reflecting the structural transformation of farming practices over recent years. Rising irrigation intensity, expansion in farm mechanisation and increased dependence on electricity and petroleum products have significantly altered the sector's energy demand profile.

Agriculture currently accounts for roughly **17-20 per cent of total electricity consumption** in India, making it one of the largest electricity-consuming sectors of the economy. Electricity demand in agriculture is dominated by irrigation pumping, which relies heavily on groundwater extraction. India operates an estimated **30 to 32 million irrigation pump sets**, of which nearly **two-thirds are electrically powered**, with the remainder relying on diesel. As a result, irrigation pumping alone accounts for the bulk of electricity demand in the sector and places a significant load on rural distribution networks.

The agriculture sector contributes roughly 17 to 20 per cent of total electricity consumption in India. The scale of irrigation-related energy demand is closely linked to the expansion of groundwater-based irrigation. More than **60 per cent of India's irrigated area** is now dependent on groundwater, compared to much lower shares in the early post-independence period. This expansion has enabled higher cropping intensity and increased agricultural output, but it has also resulted in steadily rising energy consumption. In many regions, the average efficiency of pump sets remains low, with water-to-wire efficiencies typically **below 40 per cent**. Consequently, the final energy consumed for irrigation pumping is substantially higher than the useful energy required for water lifting, amplifying the sector's overall energy demand.

In addition to electricity, agriculture remains a significant consumer of diesel. Diesel use is concentrated in mechanised field operations and in diesel-powered pump sets, particularly in regions with limited or unreliable electricity access. India's tractor stock has expanded steadily and now exceeds **nine million units**, contributing materially to rural diesel consumption. Although mechanised operations consume less energy than irrigation pumping in aggregate, diesel use in agriculture accounts for a non-trivial share of total petroleum product consumption and has implications for fuel import dependence and emissions.

This report addresses these limitations by focusing exclusively on the demand side of the agriculture sector using a bottom-up analytical framework. Energy demand is derived from physical activity indicators such as irrigation requirements, pump stock, and machinery usage, combined with technology-specific efficiency assumptions. A central feature of the analysis is the explicit estimation of useful energy demand for irrigation pumping, which is subsequently converted into final energy consumption based on pump efficiency. In our analysis, useful energy demand for irrigation is estimated at **8.06 Mtoe in 2020**, increasing to **11.38 Mtoe by 2030**, highlighting the growing scale of irrigation-related energy requirements.

The analysis evaluates agricultural energy demand under two scenarios that share identical activity assumptions but differ in their efficiency trajectories. By holding irrigation requirements and mechanisation levels constant, the study isolates the effect of improvements in pump efficiency on total energy demand. This approach provides a transparent basis for assessing the potential of efficiency-oriented interventions to moderate growth in agricultural energy consumption.

Methodology and Modelling Approach

Energy consumption in the agriculture sector is estimated using a bottom-up, equipment-based modelling approach. The methodology focuses on tractors and irrigation pumps, which together account for the majority of direct energy use in agricultural operations. By explicitly modelling these equipment categories, the approach captures the key drivers of energy demand arising from mechanisation and irrigation practices.

Tractor-related energy demand is estimated by linking the physical stock of tractors to their utilisation characteristics and fuel or electricity consumption rates. Both diesel-based and electric tractors are considered. Total energy consumption from tractors in a given year is calculated as the product of the number of tractors, the fraction of tractors by fuel type, the proportion of tractors assumed to be in active use, the fuel consumption rate or rated power of the tractor, and the average number of operating hours per year. This formulation ensures that energy demand reflects changes in equipment stock, technology composition, and usage intensity rather than being derived solely from historical fuel consumption trends.

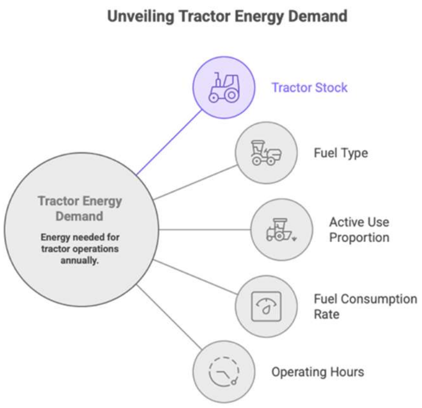

Figure 28: Parameters considered for the estimation of Tractors

The number of tractors is modelled as a time-varying stock that grows from a base-year level at an assumed compound annual growth rate, subject to an upper saturation limit. This saturation level represents the maximum feasible penetration of tractors in agriculture, beyond which growth slows and eventually stabilises. By imposing a saturation constraint, the model reflects the realistic evolution of mechanisation over time and avoids unconstrained growth in tractor numbers.

Once tractor stock is determined, total diesel and electricity consumption is calculated by applying technology-specific shares and utilisation factors. Not all tractors are assumed to be operational at all times, and a utilisation factor is therefore used to represent the share of the tractor stock that is actively used in a given year. Fuel consumption for diesel tractors is calculated using an average litres per hour value, while electricity consumption for electric tractors is calculated using their power rating. These values are multiplied by assumed annual operating hours to obtain total energy consumption.

In addition to energy use, the methodology estimates capital and operating costs associated with tractors. Capital cost per tractor is projected over time using a cost-escalation formulation that links base-year and end-year costs through an assumed rate of change. The total capital cost in a given year is calculated by multiplying the capital cost of a single tractor by the number of tractors sold that year. Operating costs are estimated separately and include only maintenance costs, assumed to be a fixed percentage of the tractor fleet's total capital cost. Fuel costs are excluded from operating costs because they are accounted for separately in the energy demand calculation.

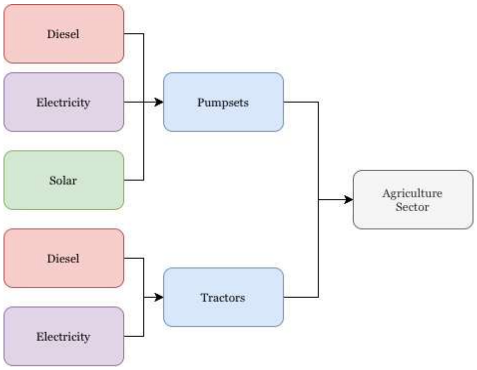

Figure 29: Technologies Considered

The evolution of tractor stock and utilisation is influenced by a range of structural drivers related to agricultural practices and rural economic conditions. These include precipitation patterns that affect cropping intensity, average landholding sizes, availability of farm labour, access to institutional credit, and the relative costs of mechanised versus manual or animal-based operations. The potential to generate additional income through renting tractors for non-agricultural uses, such as transport or construction, also contributes to higher utilisation rates. Policy measures that promote farm mechanisation are implicitly reflected in the assumed growth trajectories.

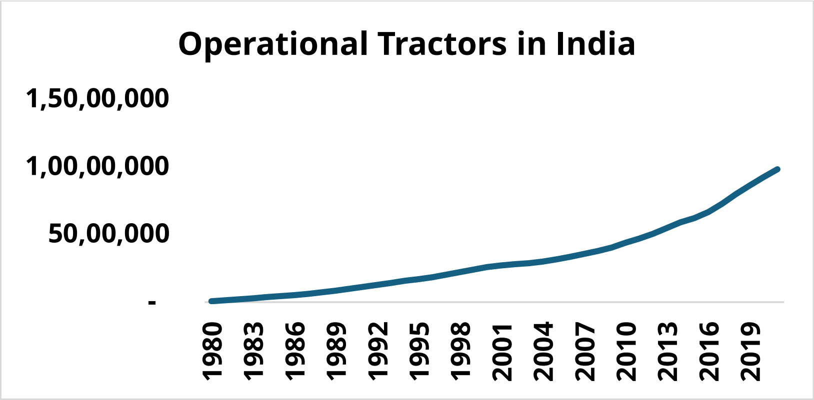

Figure 30: Demand for tractors in India

A set of explicit assumptions underpins the modelling framework. Tractor density is assumed to be 50 tractors per thousand hectares, with net sown area taken as 140.02 million hectares. According to official agricultural statistics, the number of tractors in operation in 2020 was approximately 7.77 million. Of the total stock, 60 per cent is assumed to be in active use in a given year. The average fuel consumption of an efficient diesel tractor is assumed to be 4.5 litres per hour. The average operational lifetime of a tractor is taken as 13 years. Tractor size is assumed to average 35 horsepower and is held constant over time, including under more intensive cultivation scenarios. Annual utilisation is assumed to be 500 hours per tractor, consistent with observed usage ranges in Indian agriculture.

This methodology provides a transparent, physically grounded representation of tractor-related energy demand in agriculture. By explicitly linking equipment stock, utilisation, and fuel intensity, the approach allows energy consumption to respond coherently to changes in mechanisation patterns, technology mix, and long-term structural drivers within the sector.

Scenario Definition and Design

The analysis of agricultural energy demand is undertaken using two contrasting scenarios designed to isolate the impact of technological efficiency on energy consumption. Both scenarios share a common structural framework, an activity representation, and base-year calibration. Agricultural activity levels, mechanisation pathways, and irrigation requirements are held identical across scenarios. This ensures that differences in energy demand outcomes arise solely from changes in technology performance rather than from variations in agricultural output or structural assumptions.

The **Business as Usual (BAU) scenario** represents the continuation of current practices in the agriculture sector. Under this scenario, energy demand evolves driven by projected growth in farm mechanisation and sustained irrigation activity, while technology efficiency remains at baseline levels. Tractor fuel consumption per hour, pump efficiencies, utilisation rates, and equipment lifetimes follow existing patterns, with no additional efficiency gains beyond those implicitly captured through normal equipment turnover. As a result, increases in final energy demand in the BAU scenario are primarily attributable to greater mechanisation intensity and continued reliance on irrigation pumping.

In the BAU scenario, energy demand from farm mechanisation increases in line with growth in tractor stock and utilisation. Diesel consumption per hour for tractors remains unchanged, and electricity consumption for electric tractors reflects current power ratings. Similarly, irrigation pumping energy demand increases proportionally with the useful energy required to lift water, while pump efficiencies are held constant. This scenario, therefore, provides a reference trajectory against which the impact of alternative efficiency assumptions can be assessed.

The **Ambitious scenario** explores the potential to moderate agricultural energy demand through improved technological performance. In this scenario, all energy-using technologies in the agriculture sector are assumed to achieve a **10% efficiency improvement** relative to the BAU case. This improvement is applied across the full range of technologies considered in the analysis, including diesel tractors, electric tractors, and irrigation pump sets. The efficiency enhancement reduces energy consumption per unit of activity while maintaining the same level of agricultural service delivery.

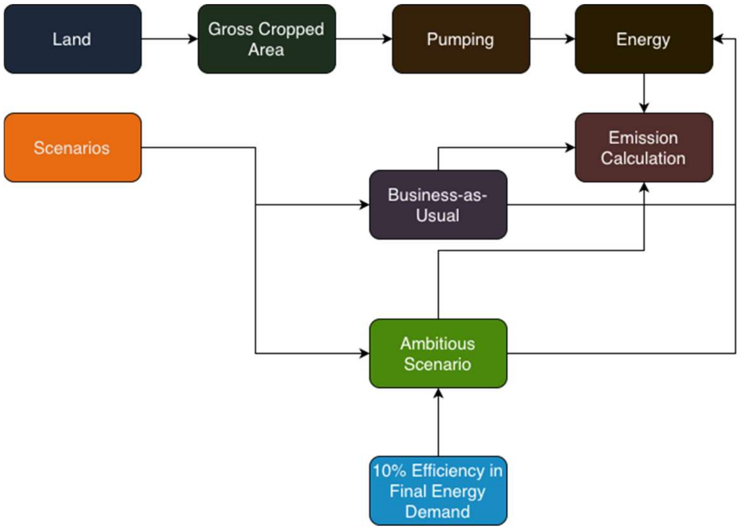

Figure 31: Methodology for Agriculture Demand Estimation

For farm mechanisation, the 10 per cent efficiency improvement is implemented through a reduction in fuel consumption per hour for diesel tractors and a corresponding reduction in electricity consumption for electric tractors. Annual operating hours, tractor stock, and the share of tractors in active use remain unchanged. Consequently, total energy demand from mechanised operations declines relative to the BAU scenario purely due to improved efficiency.

In irrigation pumping, efficiency improvement is reflected in increased pump efficiency. Useful energy demand for water lifting remains identical across scenarios. Still, final energy demand is reduced in the Ambitious scenario as less electricity or diesel is required to deliver the same irrigation service. This formulation ensures that efficiency improvements directly translate into lower final energy consumption without altering irrigation activity levels.

The Ambitious scenario does not assume structural shifts such as changes in cropping patterns, reductions in irrigated area, or accelerated electrification beyond existing trends. By limiting the scope of intervention to efficiency improvements alone, the scenario provides a conservative estimate of the potential energy savings achievable through improved technology performance.

Together, the two scenarios establish a clear analytical contrast. The BAU scenario reflects a continuation of existing trends in agricultural energy use. In contrast, the Ambitious scenario illustrates the extent to which efficiency improvements across all major technologies can moderate growth in energy demand. This scenario design enables transparent comparison and provides a robust basis for evaluating the role of efficiency-oriented interventions in shaping future agricultural energy consumption.

Farm Mechanisation Energy Demand Requirements

Farm mechanisation has emerged as a central driver of energy demand in Indian agriculture, reflecting a long-term transition away from human and animal labour towards machine-based operations. This transition is evident in the steady increase in farm power availability over the past five decades. Total farm power availability has risen from **0.37 kW per hectare in 1971–72 to 3.05 kW per hectare in 2021–22**, representing a compound annual growth rate of approximately **4.3 per cent**. This increase has been driven almost entirely by mechanised sources, particularly tractors, diesel engines, and electric motors, while the contribution of draught animals has declined sharply over the same period.

The expansion of mechanisation has fundamentally altered the composition of energy demand in agriculture. Tractors have become the dominant source of mobile farm power, with their contribution increasing from **0.02 kW per hectare in the early 1970s to nearly 1.93 kW per hectare by 2021–22**. At the same time, the contribution of diesel engines and electric motors used for stationary operations, including pumping and post-harvest activities, has increased to **0.37 kW per hectare and 0.57 kW per hectare**, respectively. This shift highlights the growing dependence of agricultural operations on commercial energy sources and explains the rising share of diesel and electricity in total agricultural energy consumption.

The increase in mechanised power availability has been closely associated with higher cropping intensity and productivity. Cropping intensity increased from **120 percent in the mid-1970s to over 141 per cent by 2021–22**, while food grain productivity rose from **0.94 tonnes per hectare to 2.27 tonnes per hectare** during the same period. Importantly, this intensification has been accompanied by a substantial rise in energy use per unit of output, with farm power per unit of food grain production increasing from **0.46 kW per tonne to 1.34 kW per tonne**. These trends indicate that improvements in agricultural output have increasingly relied on energy-intensive mechanised inputs rather than on land expansion alone.

Despite these advances, mechanisation remains uneven across agricultural operations, with important implications for energy demand growth. Overall mechanisation levels are estimated at **40 to 45 per cent**, with relatively high penetration in land preparation and harvesting for major cereals, but much lower adoption in operations such as sowing, weeding, and harvesting for non-cereal crops.

As these under-mechanised operations expand, particularly among small and marginal farmers, additional demand for tractor-mounted and self-propelled machinery is expected, leading to further increases in diesel and electricity consumption.

Farm size dynamics also play a critical role in shaping mechanisation-related energy demand. The net sown area per tractor has declined sharply from **487 hectares in 1975–76 to around 15 hectares in 2021–22**, indicating a much denser deployment of machinery. While this has improved the timeliness of operations, it has also increased aggregate energy consumption, as more machines operate on smaller landholdings. The increasing prevalence of custom hiring models has further increased tractor and other machinery utilisation rates, intensifying fuel and electricity use per unit of equipment stock.

Looking ahead, mechanisation is expected to deepen further, driven by labour shortages, declining average landholdings, and policy support for the adoption of farm machinery. The agricultural machinery market in India is projected to grow at a compound annual rate of **8.5 per cent**, significantly faster than global averages, driven by increased emphasis on non-tractor machinery such as power tillers, planters, harvesters, and precision equipment. This evolution suggests that energy demand from farm mechanisation will continue to grow, not only through an expansion of tractor stock but also through the diversification of mechanised operations that rely on both diesel and electricity.

In this context, energy demand associated with farm mechanisation is best understood as a function of equipment stock, utilisation intensity, and power ratings rather than as a fixed proportion of agricultural output. Explicitly accounting for these drivers is therefore essential for accurately estimating current and future energy requirements of the agriculture sector. The methodology adopted in this report reflects this perspective by linking mechanisation trends directly to fuel and electricity demand through physical activity and equipment-based parameters.

Modelling Tool Implementation

The modelling framework is implemented using a bottom-up, accounting-based energy demand modelling tool that allows explicit representation of agricultural activities, equipment stocks, and technology-specific energy intensities. The tool is designed to translate physical activity drivers into final energy demand through transparent and internally consistent calculations, making it well-suited for analysing sectors such as agriculture, where energy use is closely tied to equipment utilisation and service delivery.

Agricultural energy demand is represented using a hierarchical structure that disaggregates consumption by end use and equipment type. Farm mechanisation is explicitly modelled through tractor stock and utilisation, while irrigation-related demand is captured through pumping stock, useful energy demand for pumping, and efficiency parameters for different types of pumpsets. This structure ensures that the major source of energy demand is linked to the physical processes that generate it, rather than inferred from aggregate energy statistics.

All the key drivers of energy demand are implemented as time-varying parameters. Equipment stocks, such as the number of tractors and pumpsets, are represented as physical quantities that evolve based on growth and saturation assumptions. Utilisation parameters, including the share of different equipment in active use and annual operating hours, are applied to convert equipment stocks into activity levels. Technology characteristics, such as fuel intensity and efficiency, are specified separately for different equipment types, allowing endogenous calculation of fuel-specific energy demand.

Energy demand calculations follow a consistent accounting logic across all end uses. For farm mechanisation, total energy consumption is calculated by multiplying equipment stock, utilisation rates, fuel shares, and energy intensity parameters. For irrigation pumping, useful energy demand is specified independently and converted into final energy demand by applying average pump efficiencies. This distinction between useful and final energy ensures that efficiency improvements reduce energy consumption without altering the underlying level of agricultural service delivered.

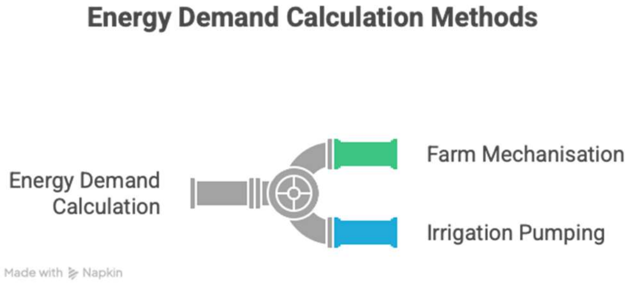

Figure 32: Energy Demand Calculation Method

Scenario analysis is implemented by maintaining a fixed model structure and selectively modifying input assumptions. Activity drivers such as tractor stock growth, utilisation rates, and irrigation requirements are held constant across scenarios unless explicitly altered. Differences between scenarios arise from changes in technology performance parameters, particularly efficiency trajectories. This approach ensures that variations in model outputs can be traced directly to changes in clearly defined assumptions rather than to structural changes in the model.

The modelling tool aggregates end-use level energy demand across equipment types and fuels to generate total agricultural energy consumption by fuel and by activity. Outputs are produced as time series, enabling comparison across years and scenarios. The accounting structure ensures full transparency, allowing intermediate results such as equipment activity levels and efficiency-adjusted energy use to be examined alongside aggregated outcomes.

Overall, the implementation of the modelling tool provides a robust and interpretable platform for analysing agricultural energy demand. By grounding calculations in physical drivers and equipment characteristics, the framework supports consistent scenario comparison. It enables clear attribution of changes in energy demand to mechanisation trends, efficiency improvements, and technology adoption patterns.

Comparison of Scenarios and Energy Savings

The comparison between the Business as Usual (BAU) and Ambitious scenarios highlights the extent to which improvements in technology efficiency can moderate growth in agricultural energy demand, even when underlying agricultural activity and mechanisation levels remain unchanged. Since both scenarios share identical assumptions on tractor stock, utilisation, and irrigation requirements, the observed differences in energy demand are attributable solely to efficiency improvements.

Under the BAU scenario, total final energy demand in agriculture increases steadily over time, driven by rising mechanisation and sustained irrigation requirements. Total agricultural energy demand rises from **32.3 Mtoe in 2020** to **43.6 Mtoe by 2030** and continues to increase thereafter. This growth reflects the combined effects of expanding tractor use and increasing energy requirements for irrigation pumping, with efficiency parameters remaining at baseline levels.

In contrast, the Ambitious scenario demonstrates a markedly lower energy demand trajectory. With a uniform **10 percent improvement in efficiency across all agricultural technologies**, total energy demand rises more slowly, reaching **36.1 Mtoe in 2030**. This represents an absolute reduction of approximately **7.4 Mtoe in 2030** relative to the BAU scenario. The magnitude of this difference underscores the sensitivity of agricultural energy demand to technology performance, particularly in energy-intensive activities such as irrigation, pumping and mechanised field operations.

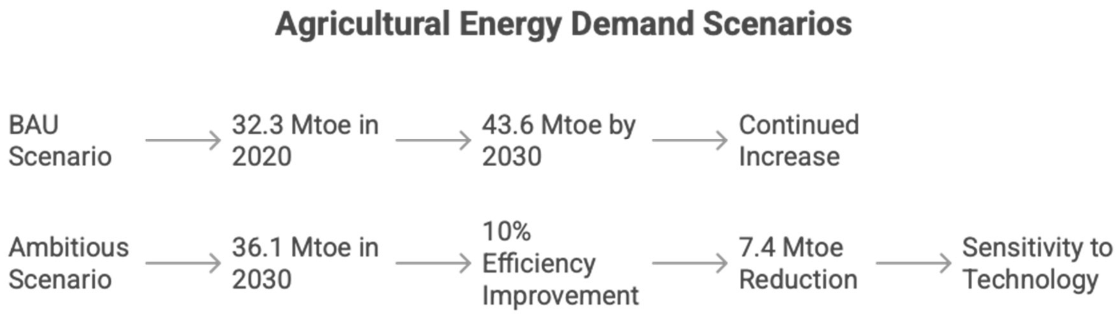

Figure 33: Different Agriculture Scenarios

The energy savings in the Ambitious scenario accumulate progressively over time. While the difference between scenarios is modest in the early years, it widens as agricultural activity scales up. By the mid-term, efficiency improvements lead to substantial reductions in final energy demand, even though the same level of irrigation service and mechanised output is delivered in both scenarios. This indicates that efficiency improvements not only reduce energy consumption in absolute terms but also dampen the rate of demand growth over the long run.

A large share of the observed savings arises from reduced electricity and diesel consumption associated with irrigation pumping. Because irrigation demand is modelled in terms of useful energy requirements, improvements in pump efficiency directly translate into lower final energy consumption without affecting water delivery. Similarly, reductions in fuel consumption per hour for tractors contribute to lower diesel demand from farm mechanisation, although the absolute impact is smaller than that of irrigation because pumping accounts for a larger share of total agricultural energy use.

By design, the Ambitious scenario does not assume changes in cropping patterns, reductions in irrigated area, or shifts in mechanisation intensity. As a result, the energy savings identified here can be interpreted as conservative estimates of the potential achievable through efficiency improvements alone. The results clearly demonstrate that even modest, uniform efficiency gains across technologies can yield significant reductions in aggregate agricultural energy demand.

Overall, the comparison of scenarios highlights the central role of efficiency in shaping future agricultural energy use. While mechanisation and irrigation requirements continue to drive demand upward in both scenarios, efficiency improvements significantly reduce the scale of this increase. These findings provide a strong quantitative basis for prioritising efficiency-oriented interventions in the agriculture sector, particularly in irrigation pumping and farm machinery, as part of broader energy planning and demand management strategies.

Food-Energy-Water (FEW) Nexus for Strategic Crop Substitution

The current landscape of Indian agriculture is defined by a deep, often strained relationship among food production, energy consumption, and water availability. As our preceding analysis established, the sector's energy appetite, accounting for 17% to 20% of the nation's total electricity, is largely driven by a single, relentless activity: groundwater extraction for irrigation. While the "Ambitious Scenario" demonstrates how technical efficiency can mitigate this load, a more fundamental transformation emerges when we look beyond the machinery and toward the crops themselves. By strategically substituting water-intensive rice with climate-resilient millets, we can address the root cause of resource depletion at the source.

The Cycle of Thirst and Power

At the heart of the current crisis is the staggering resource requirement of traditional paddy cultivation. In our current model, producing just one kilogram of rice requires approximately 3,000 litres of water, a requirement that forces farmers to keep irrigation pumps running for extended periods. This demand is further compounded by a 60% reliance on irrigation for rice, which places a heavy, consistent load on rural distribution networks.

When we consider that the average pump set operates at a "wire-to-water" efficiency of less than 40%, the story becomes one of systemic waste. We are not just lifting water; we are consuming massive amounts of electricity to lift water that the crop consumes at an unsustainable rate. If left unchecked, this cycle is projected to drive agricultural electricity demand to 18.6 Mtoe by 2047. However, the introduction of millets changes this narrative entirely.

Millets: The Structural Intervention

Millets represent a fundamental shift in the Food-Energy-Water nexus. Often called "Future Smart Crops," millets require only 350 litres of water per kilogram produced, a staggering 88% reduction in water footprint compared to rice. This "volumetric saving" of 2,650 litres per kilogram does more than just save water; it also serves as a structural demand-side management tool for the power grid.

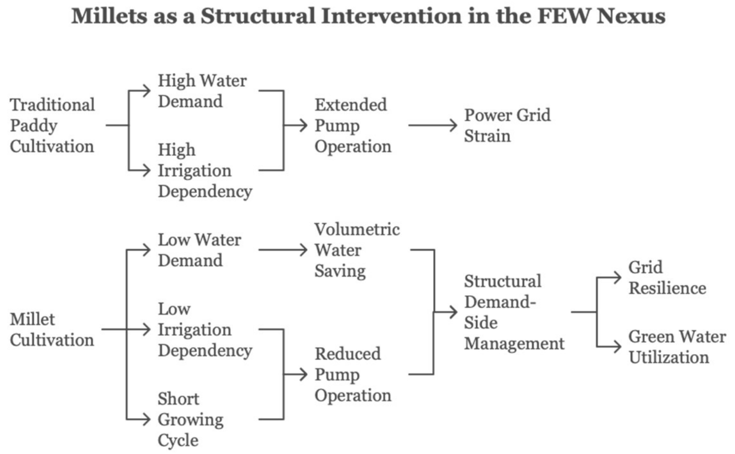

Figure 34: Different Agriculture Scenarios

Because millets have a significantly lower irrigation dependency (only 15%) and a much shorter growing cycle, averaging 75 days, compared to the 150 days required for rice, the total operating hours for pump sets are slashed. This reduction in pumping time is arguably the most effective way to bypass the inherent inefficiencies of the current pump stock. A shift toward millets doesn't just make the grid more resilient; it prevents the need for energy consumption altogether by utilising "green water" (rainfall) more effectively.

Beyond the Pump: The Carbon and Chemical Footprint

The story of the FEW nexus extends beyond the immediate pull of electricity. The energy intensity of our food is also "embedded" in the chemicals and carbon we release during production. Rice cultivation is an energy-intensive process that leaves a heavy footprint, estimated at 3.5 kg CO_2eq per kilogram of grain. Much of this is tied to the 250 kg/ha of NPK fertilisers required to sustain high-yield paddy fields, a chemical input itself produced by high-energy industrial manufacturing.

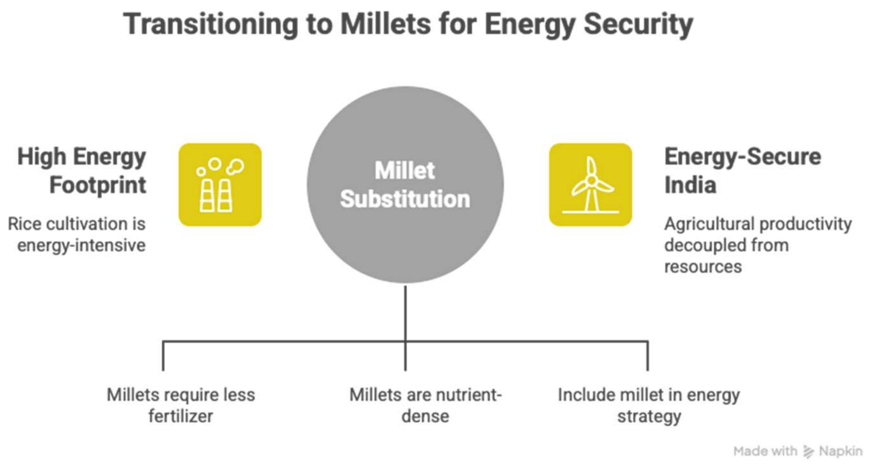

Figure 35: Transitioning to Millets

Millets offer a cleaner alternative, requiring only 50 kg/ha of fertiliser and emitting just 0.5 kg CO_2eq per kilogram. By making this transition, the agricultural sector achieves a six-fold reduction in greenhouse gas emissions while simultaneously improving nutritional outcomes. Millets provide superior protein, fibre, and micronutrient density, ensuring that every unit of energy and water invested in the field yields a higher "nutritional return" for the population.

Integrating millet substitution into the national energy strategy is not merely an agricultural recommendation; it is a prerequisite for long-term energy security. While we must continue to pursue the 10% technical efficiency gains outlined in the Ambitious Scenario, crop diversification offers a path to address the *root cause* of energy stress. By fundamentally reducing the volume of water that needs to be lifted, the FEW Nexus approach provides a roadmap to a future where agricultural productivity is decoupled from resource exhaustion, ensuring a climate-resilient and energy-secure India.

Results

This section presents the results of the agricultural energy demand analysis under the Business-as-Usual (BAU) and Ambitious scenarios. Results are reported in terms of total final energy demand, fuel-wise composition, and end-use contributions, with particular emphasis on farm mechanisation and irrigation pumping. All values are expressed in million tonnes of oil equivalent.

Total Agricultural Energy Demand

Under the BAU scenario, total final energy demand in the agriculture sector increases substantially over the projection period. In 2020, total agricultural energy demand is estimated at **32.29 Mtoe**, of which **9.26 Mtoe** is attributable to tractors and **23.03 Mtoe** to irrigation pump sets. Energy demand continues to rise steadily, reaching **43.59 Mtoe by 2030** and further increasing to **61.81 Mtoe by 2047**.

This growth reflects rising mechanisation intensity and increasing irrigation energy requirements, with no additional efficiency improvements assumed beyond baseline conditions.

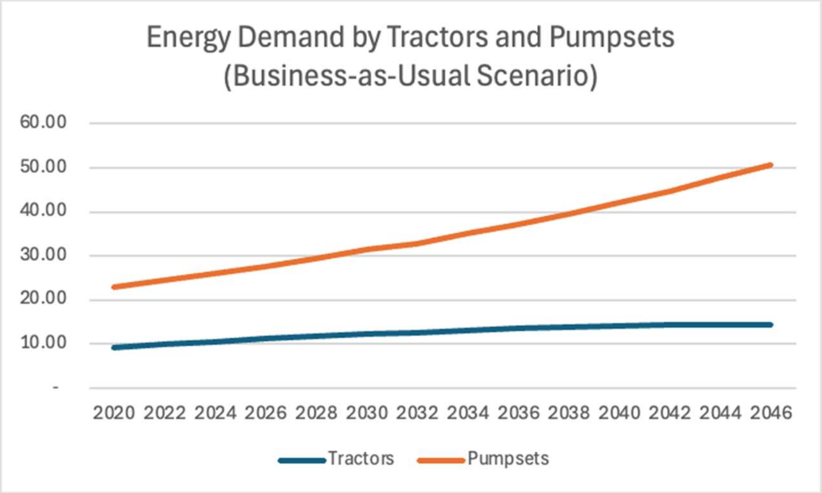

Figure 36: Energy Demand in the BAU Scenario

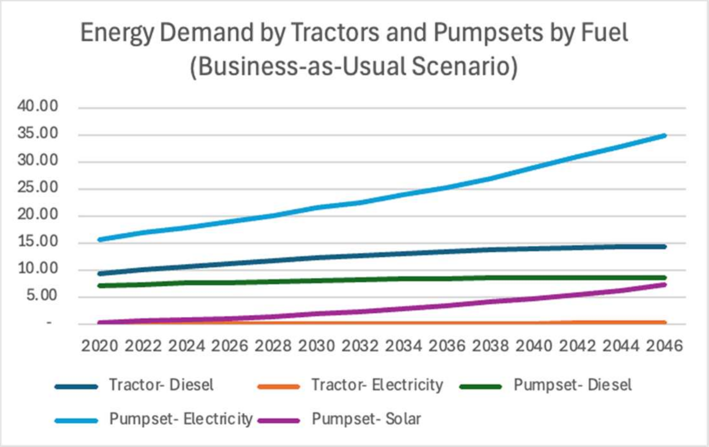

Figure 37: Energy Demand by Fuel Mix in BAU Scenario

In contrast, the Ambitious scenario exhibits a significantly moderated growth trajectory. With a uniform **10 per cent improvement in efficiency across all agricultural technologies**, total energy demand in 2020 is **29.06 Mtoe**, already lower than in the BAU case due to immediate efficiency gains. By 2030, total energy demand under the Ambitious scenario reaches **36.15 Mtoe**, compared to **43.59 Mtoe** in the BAU scenario. By 2047, total energy demand in the Ambitious scenario is **55.24 Mtoe**, representing an absolute reduction of approximately **6.57 Mtoe** relative to the BAU scenario.

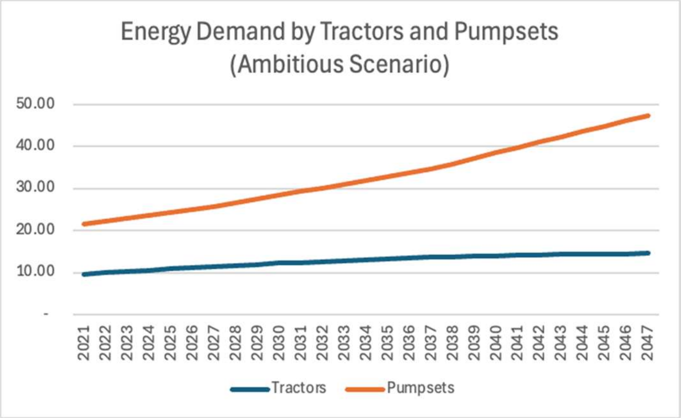

Figure 38: Energy Demand in Ambitious Scenario

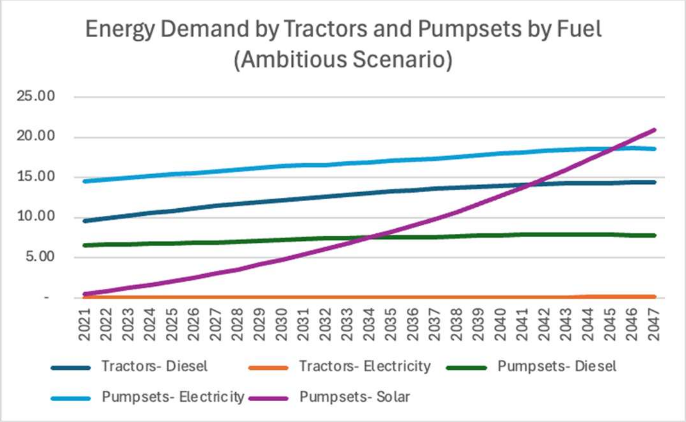

Figure 39: Energy Demand by Fuel Mix in Ambitious Scenario

End-use Contributions

Irrigation pumping accounts for the majority of agricultural energy demand in both scenarios. In the BAU case, energy consumption from pump sets increases from **23.03 Mtoe in 2020** to **31.72 Mtoe in 2030**, and further to **47.28 Mtoe by 2047**. Electricity accounts for the largest share of pumping energy demand, rising from **15.67 Mtoe in 2020** to **18.60 Mtoe by 2047**, while diesel use for pumping remains significant, rising from **7.13 Mtoe in 2020** to **7.75 Mtoe by 2047**. A small but growing contribution from solar pumping is also observed, rising from **0.22 Mtoe in 2020** to **20.93 Mtoe by 2047**.

In the Ambitious scenario, the pump set energy demand is consistently lower across all years. Total pumping energy demand in 2020 is **21.03 Mtoe**, increasing to **27.34 Mtoe in 2030** and **41.42 Mtoe by 2047**. The reduction relative to BAU arises from higher pump efficiency, which reduces final energy consumption for the same level of useful energy required for water lifting. Electricity demand for pumping is substantially reduced, while diesel and solar contributions follow similar trajectories, albeit at lower absolute levels.

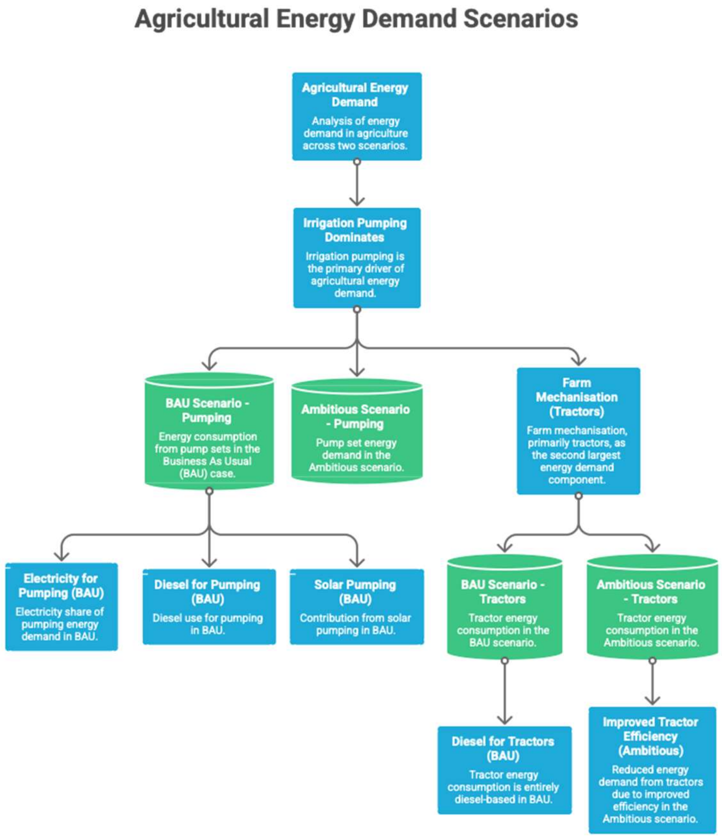

Figure 40: End Use Flow

Farm mechanisation, primarily represented by tractors, is the second-largest component of agricultural energy demand. Under BAU, tractor energy consumption in 2020 is **9.26 Mtoe**, entirely diesel-based. This increases steadily over time, reaching **11.87 Mtoe in 2030** and **14.53 Mtoe by 2047**, reflecting growth in tractor stock and utilisation. Electricity use from tractors remains negligible in the BAU scenario.

In the Ambitious scenario, energy demand from tractors is reduced due to improved efficiency. Tractor energy consumption in 2020 is **8.03 Mtoe**, rising to **8.81 Mtoe in 2030** and **10.96 Mtoe by 2047**. The difference relative to BAU widens over time, highlighting the cumulative impact of efficiency improvements on mechanisation-related energy demand.

Fuel-wise Energy Demand

Electricity and diesel dominate agricultural energy use across both scenarios. In the BAU scenario, electricity demand grows rapidly due to increasing reliance on electric pump sets, reaching **18.60 Mtoe by 2047**. Diesel consumption also increases steadily, driven by both tractors and diesel pump sets, reaching **14.38 Mtoe by 2047**. Solar energy contributes an increasing share over time, reflecting the gradual adoption of solar pumping technologies.

In the Ambitious scenario, electricity and diesel demand are both lower across the projection period. Electricity consumption for irrigation pumping declines relative to BAU due to higher efficiency, while diesel demand from tractors is reduced due to lower fuel consumption per hour. Solar energy follows a similar expansion path as in BAU but contributes to a lower total energy requirement due to efficiency gains in conventional technologies.

Scenario Comparison and Energy Savings

The divergence between the BAU and Ambitious scenarios becomes more pronounced over time. By 2030, the Ambitious scenario delivers an absolute energy saving of approximately **7.44 Mtoe**, representing a reduction of nearly **17 per cent** relative to the BAU scenario. By 2047, cumulative energy savings continue to increase, with the Ambitious scenario consuming **over 10 per cent less energy** than BAU while delivering the same level of agricultural services.

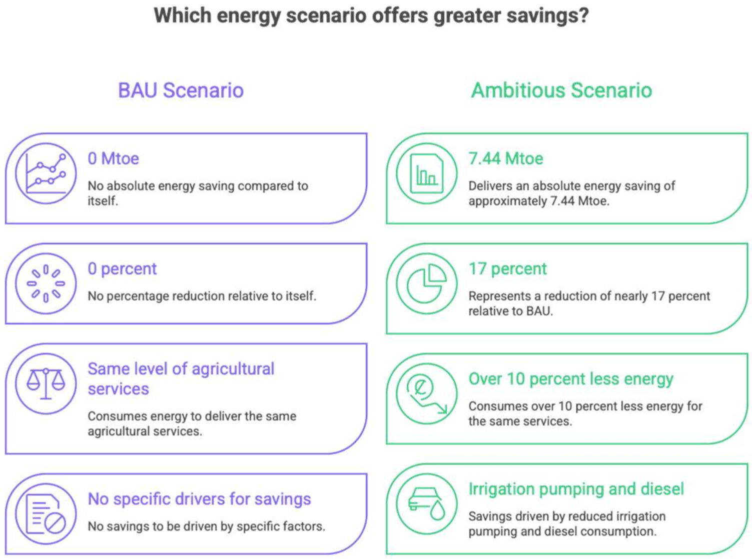

Figure 41: Scenarios for Energy Saving

These savings are driven predominantly by reductions in irrigation pumping energy demand, followed by lower diesel consumption from farm mechanisation. Because underlying agricultural activity, equipment stock, and utilisation assumptions are identical across scenarios, the results demonstrate that efficiency improvements alone can significantly moderate the growth of agricultural energy demand.

Key Insights

The results clearly indicate that agricultural energy demand is highly sensitive to technology efficiency. Irrigation pumping remains the dominant driver of energy consumption, and improvements in pump efficiency yield large reductions in final energy demand. Farm mechanisation accounts for a smaller but steadily growing share of energy use, and tractor efficiency improvements provide meaningful cumulative savings. Together, these findings highlight the critical role of efficiency-oriented interventions in shaping future trajectories of agricultural energy demand.

Under the Business-as-Usual scenario, agricultural energy demand increases steadily over the projection period, driven by rising mechanisation and sustained irrigation requirements. Electricity demand from irrigation pumping and diesel consumption from tractors together account for the bulk of this growth. Without targeted interventions, these trends imply increasing pressure on rural electricity infrastructure, higher fuel consumption, and rising system costs.

The Ambitious scenario demonstrates that efficiency improvements can significantly moderate this growth. A uniform 10 percent improvement in efficiency across tractors and irrigation pump sets delivers substantial reductions in total energy demand, amounting to several million tonnes of oil equivalent by 2030 and growing thereafter. Importantly, these savings are achieved without reducing agricultural output, mechanisation levels, or irrigation services. This finding highlights the efficiency of this approach as a powerful, low-risk instrument for managing agricultural energy demand.

The analysis also illustrates the importance of distinguishing between useful energy demand and final energy consumption, particularly in irrigation pumping. Improvements in pump efficiency directly reduce electricity and diesel consumption while maintaining the same level of water delivery. Similarly, efficiency gains in tractors reduce fuel use per hour of operation, dampening the energy implications of increasing mechanisation. Together, these effects show that technology performance plays a decisive role in determining long-term energy demand trajectories in agriculture.

Looking ahead, the findings point to several priorities for future action. First, efficiency-oriented interventions in irrigation pumping and farm mechanisation should be elevated as central elements of agricultural and energy policy. Second, demand-side efficiency should be explicitly integrated into energy planning processes to avoid overinvestment in supply-side infrastructure. Third, future modelling efforts should extend the analysis to include additional agricultural end uses, such as post-harvest processing and emerging technologies, as well as regional disaggregation to capture spatial heterogeneity in energy use.

Further work can also explore the interaction between efficiency improvements and renewable energy deployment, particularly in the context of solar-powered irrigation. While renewable technologies can reduce dependence on grid electricity and fossil fuels, their energy and water use implications depend critically on efficiency and system design. Integrating these dimensions into future analyses will be essential for developing balanced and sustainable agricultural energy strategies.

Overall, the findings suggest that agricultural energy demand should be addressed through a combination of demand-side efficiency measures and coordinated planning across the energy and agriculture sectors. Efficiency improvements in irrigation pumping and farm mechanisation emerge as priority areas for intervention, offering significant energy savings while supporting agricultural productivity and resilience.

5. Energy Supply & Associated GHG Emissions

This section provides a comprehensive assessment of India's energy supply system, focusing on the primary energy resources, coal, oil, and natural gas, and their transformation into the electricity and refined products that power the national economy. Understanding the evolution of this primary energy mix and the infrastructure required to deliver it is critical for evaluating the feasibility and environmental impact of India's long-term developmental pathways. While energy supply in its entirety includes multiple fuels and transformation pathways, this report focuses specifically on the electricity supply sector. Electricity serves as the principal medium through which emission reduction is realised across end-use sectors such as transport, industry, and buildings. The analysis therefore examines electricity generation from a range of sources, including coal, natural gas, solar, wind, hydro, nuclear, biomass, and waste-to-energy. Oil, although an important component of the broader energy system, is not examined in detail in this section as its primary use lies outside the electricity sector.

The analysis utilises the LEAP–ACPET modelling framework to examine electricity supply dynamics through 2070. The study constructs two distinct pathways: a Business-as-Usual (BAU) scenario, which projects current technology trends and policy frameworks, and a Low-carbon scenario, which explores an accelerated shift toward non-fossil sources and improvements in thermal plant efficiencies. The assessment quantifies electricity generation requirements, installed capacity trajectories, fuel inputs, and the associated greenhouse gas emissions under each scenario.

Coal and natural gas remain central to the electricity generation mix, with coal continuing to play a dominant role in ensuring baseload supply, while natural gas contributes to the diversification of the generation portfolio. Non-fossil sources, including solar, wind, hydro, nuclear, biomass, and waste, are evaluated for their expanding role in shaping the future electricity system. The analysis tracks the transformation of these primary energy inputs into electricity, accounting for conversion efficiencies and the resulting emissions profile.

The results highlight that, although a transition towards cleaner generation technologies can significantly reduce the emissions intensity of electricity supply, the scale of projected growth in electricity generation may lead to an increase in absolute emissions in the near term. The Low-carbon pathway demonstrates that by 2070, a strategic shift in the generation mix can avoid nearly 1,000 $MtCO_2eq$ of annual emissions compared to the BAU scenario.

The following sub-sections present the detailed electricity supply methodology, generation trajectories by source, as well as the associated capacity and emissions implications. Together, these analyses provide a focused and coherent assessment of the evolution of India's electricity supply sector within the broader context of the national energy system.

5.1. Electricity Supply

Introduction

Electricity occupies a central position in India's development pathway and its long-term energy transition. As the country advances towards its vision of becoming a developed economy by 2047 and achieving net-zero emissions by 2070, the scale, structure, and evolution of the power sector will play a decisive role in shaping both economic and environmental outcomes. Electricity is not only a critical input to industrial production and services-led growth, but also the primary medium through which emission mitigation of end-use sectors, including transport and industry, is expected to occur.

Over the past decade, India's electricity system has expanded rapidly to meet rising demand. Total electricity consumption increased from approximately 785 billion units (BU) in 2011–12 to around 1,440 BU in 2022–23, reflecting sustained economic growth, rising per capita Consumption, and expanding access (Central Electricity Authority [CEA], 2025). Installed capacity has grown commensurately, with the power system diversifying progressively beyond conventional thermal generation. Renewable energy sources, particularly solar and wind, have seen accelerated deployment, supported by targeted policy initiatives. As of 2024, non-fossil capacity accounted for approximately 47 per cent of total installed capacity, a substantial and growing share; however, coal continues to dominate actual electricity generation owing to its role in providing reliable, dispatchable power (Ministry of Power, 2024).

Despite this progress, India's electricity system remains at a relatively early stage of development per capita, with consumption levels significantly below the global average and well below those of several emerging peers (International Energy Agency [IEA], 2024). This implies that substantial demand growth is both expected and structurally necessary to support improvements in living standards, industrial expansion, and digital infrastructure. Emerging demand drivers, including electric mobility, data centres, and increased cooling requirements, are likely to further accelerate electricity consumption over the coming decades.

At the same time, the structure of the electricity supply system poses a critical challenge for India's energy transition. Coal-based generation currently accounts for approximately 74 per cent of electricity produced, reflecting the historical availability of domestic coal resources, existing infrastructure, and the continuing requirement for firm and dispatchable power (Central Electricity Authority [CEA], 2024). This dependence on coal carries significant implications for greenhouse gas emissions, as the power sector accounted for approximately 54 per cent of India's total energy-related CO2 emissions in 2023, making it the single largest contributing sector (International Energy Agency [IEA], 2025). As India pursues its climate commitments, the pace and extent of the transition away from coal, and the corresponding expansion of low-carbon generation, become central questions for energy policy.

In this context, understanding how electricity supply evolves under alternative pathways is essential. The future trajectory of the power sector will depend not only on the scale of electricity demand but also on the composition of the generation mix, the performance characteristics of different technologies, and the infrastructure required to support them. Shifts in the relative shares of coal, renewables, nuclear, and other sources will carry significant implications for installed capacity requirements, fuel consumption, and emissions outcomes.

This paper presents a forward-looking assessment of India's electricity supply under two alternative scenarios: a Business-as-Usual (BAU) pathway and a Low-carbon pathway. Both scenarios are anchored in a common macroeconomic and electricity demand trajectory, ensuring that differences in outcomes are attributable to variations in the generation mix and technology assumptions rather than underlying demand conditions. This enables a cleaner comparison of how alternative supply-side pathways influence capacity requirements, fuel use, and emissions over the long term.

The analysis adopts a system-level approach to modelling electricity supply, implemented within the Low Emissions Analysis Platform (LEAP) framework. Rather than focusing on plant-level dynamics or optimisation-based dispatch, the framework emphasises internally consistent relationships between electricity generation, installed capacity, and technology-specific performance parameters, linking generation, capacity, fuel use, and emissions within a unified analytical structure. This ensures coherence across key components of the electricity system and provides a transparent representation of how different supply pathways translate into physical and environmental outcomes.

By examining the evolution of electricity supply under these alternative scenarios, this paper provides a quantitative, system-level assessment of India's power sector transition through to 2070. The results illustrate how different generation pathways translate into divergent outcomes across capacity expansion, fuel dependence, and emissions trajectories, offering insights into the trade-offs inherent in balancing development needs against climate objectives.

Objectives

The primary objective of this analysis is to develop a structured, internally consistent outlook of India's electricity supply across alternative transition pathways. A central question guiding this analysis is: how do different generation mixes meet projected electricity requirements, and what are the long-term implications for installed capacity, fuel use, and greenhouse gas emissions? In addressing this, the analysis further asks how contrasting supply-side pathways diverge in their energy and emissions outcomes, and what these differences imply for India's development and climate commitments. Together, these questions motivate a systematic comparison of how supply-side choices shape long-term outcomes under alternative scenarios.

Specifically, the electricity supply module is designed to:

- estimate total electricity generation requirements and their allocation across major generation technologies under alternative scenarios;
- derive installed capacity requirements by technology using technology-specific utilisation assumptions, ensuring internal consistency between generation and capacity;

- assess fuel requirements for thermal generation, particularly coal and natural gas, based on process efficiency assumptions;
- estimate direct greenhouse gas emissions from electricity generation using standard emission factors, expressed in carbon dioxide equivalent terms;
- Compare the evolution of the power sector under a Business-as-Usual (BAU) and a Low-carbon scenario, focusing on differences in generation mix, capacity expansion, fuel dependence, and emissions trajectories.

Together, these objectives aim to ensure that the analysis captures the key physical and environmental dimensions of electricity supply in a coherent, traceable manner. The modelling framework is structured to maintain consistency across generation, capacity, fuel, and emissions accounting, enabling meaningful comparisons across scenarios and over time.

The analysis aims to provide a transparent, analytically grounded representation of the electricity supply system. The results are designed to inform discussions on energy planning, infrastructure requirements, and climate strategy within the broader context of India's development and net-zero commitments.

Methodology

This section describes the analytical structure used to represent electricity supply, covering the system boundary, modelling logic, technology representation, and the relationships governing generation, capacity, fuel use, and emissions. Since the electricity supply analysis is linked to an underlying demand projection, the methodology first explains the upstream logic used to arrive at generation requirements before detailing the supply-side assumptions.

1. Analytical Framework and System Boundary

The electricity supply analysis is developed within an integrated long-term framework that links economic growth, electricity demand, and power sector outcomes. Electricity demand is first estimated using sectoral economic projections and historical relationships between economic output and electricity consumption. These demand estimates are subsequently converted into gross electricity generation requirements after accounting for system losses and auxiliary Consumption[2]. The analysis then focuses on how gross generation is allocated across technologies and how this translates into installed capacity, fuel requirements, and emissions.

The system boundary covers electricity generation and associated direct emissions across the major technologies currently shaping, and likely to continue shaping, India's electricity system. These include coal, gas, renewable energy sources, hydro, nuclear, biomass, and waste-to-energy. The analysis does not simulate plant-level dispatch, hourly balancing, or detailed regional power flows. Instead, it adopts

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[2] Adapted from *India's Viksit Bharat @2047 and Net Zero @2070 Goals: Impact on Coal Economy,* ACPET, authored by Ms Anvesha Adhikari, Ms Navya, Ms Anjali Goyal, Dr Anandajit Goswami, and Mr Rakesh Kacker.

a system-level accounting approach suited to examining long-term structural shifts in the generation mix.

A defining feature of the framework is internal consistency. Installed capacity is not specified independently of generation; rather, it is derived from generation requirements using technology-specific utilisation assumptions. Fuel use is then calculated from generation and efficiency, and emissions are estimated from fuel use and emission factors. This sequential structure ensures that changes in one part of the system propagate consistently through the others.

The analytical flow can be summarised as follows:

Economic growth → Sectoral electricity demand → Final electricity demand → Gross electricity generation → Technology-wise generation → Installed capacity → Fuel input → Greenhouse gas emissions

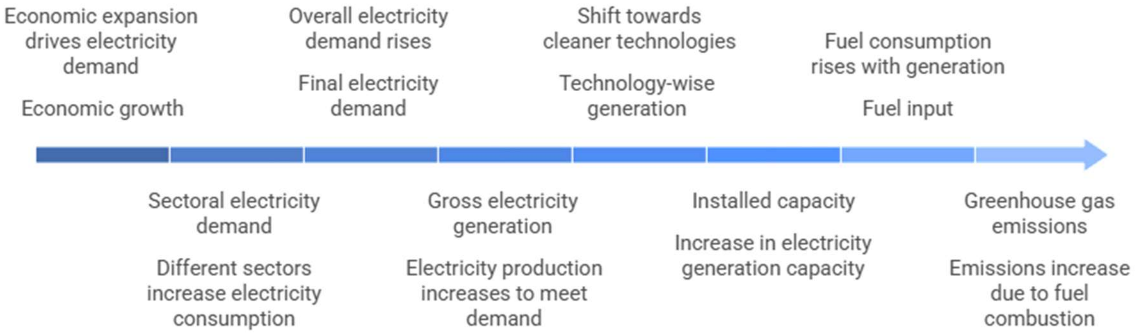

Figure 42: Flow of Calculations

This structure is particularly suited to the Indian context, where future electricity demand is expected to rise substantially, and the implications of that increase will depend fundamentally on the composition of the generation mix. The framework, therefore, allows demand growth and supply-side transformation to be examined together within a coherent analytical framework.

The analysis spans the period 2023-24 to 2070. Within the LEAP framework, 2023-24 serves as the base year, with projections extending to 2070 as the end year, consistent with India's net-zero target horizon. The underlying demand framework draws primarily on 2022-23 as its base year for macroeconomic and electricity consumption data, with technology-specific parameters, such as generation shares and utilisation factors, referenced to 2023-24 when more recent data are available.

2. Modelling Approach

The electricity supply outlook is developed using the Low Emissions Analysis Platform (LEAP), employed here as a long-term accounting framework for representing generation, fuel use, and emissions under alternative scenarios.

The approach is top-down and scenario-based. Total gross electricity generation is treated as the starting point for the supply module and is allocated across generation technologies based on scenario-specific source-share assumptions. Installed capacity is derived by applying technology-specific capacity utilisation or plant load factors. Fuel input is estimated based on process efficiency assumptions, and emissions are calculated using fuel-specific emission factors.

This modelling choice is deliberate. The purpose of the analysis is to examine how alternative generation pathways shape long-term system requirements, not to identify a least-cost dispatch solution. A dispatch or optimisation model would require detailed assumptions regarding costs, temporal variability, ramping, storage, transmission constraints, and unit-level operations. While such questions are important, they fall outside the scope of the present analysis. For long-term structural assessment, the accounting framework adopted here offers a transparent and tractable representation of how supply-side choices drive system-level outcomes.

3. Technology Classification and Representation

The electricity system is represented through the following technology categories: coal (including lignite), natural gas, diesel, solar, wind, large hydro, small hydro, biomass, waste-to-energy, and nuclear.

These categories are derived from broader source groupings in the demand-linked generation framework: steam, renewable energy sources, and others. Still, they are disaggregated further to capture differences in performance, utilisation, efficiency, and emissions characteristics. The "others" category is separated into large hydro, nuclear, gas, and diesel, enabling the model to distinguish between sources that may be grouped in high-level energy balances but differ significantly in operational behaviour and long-term system role. Diesel is retained in the classification but excluded from explicit LEAP modelling given its negligible share in the electricity mix.

Bio-power is divided into biomass and waste-to-energy to reflect differences in fuel characteristics, operational assumptions, and emissions treatment. Hydropower is split into large and small hydro because these technologies differ in scale, utilisation, and system role. This level of disaggregation improves the realism of the electricity supply representation without introducing unnecessary complexity. It ensures that major inter-technology differences are visible in the resulting capacity, fuel, and emissions estimates.

4. Estimation of Capacity

Installed capacity is estimated through a chain of assumptions linking macroeconomic growth, sectoral demand, generation requirements, generation mix, and technology utilisation.

Macroeconomic Growth Trajectory

The long-term demand outlook is based on a two-phase growth trajectory. Up to 2047, GDP is assumed to grow at a compound annual rate of 7 per cent, consistent with the medium-growth trajectory in NITI Aayog's India Energy Security Scenarios V3. From 2047 to 2070, growth is assumed to moderate to approximately 5 per cent annually, reflecting a transition towards a more mature, high-income economy. This trajectory provides the macroeconomic foundation for projecting future electricity demand across the analysis period.

Structural Composition of the Economy

Alternative sectoral shares in GDP are considered to represent possible structural transformation, particularly the prospect of manufacturing-led growth. IESS V3 informs the higher-industry pathway and reflects the policy emphasis on manufacturing-led development. However, the analysis indicates that moderate variation in sectoral composition has a smaller effect on long-term capacity requirements than variation in the electricity generation mix. Accordingly, for the extended analysis to 2070, a representative structure with industry at 30 per cent of GDP is adopted.

Sector	2022 Base Year	Low Industry Growth	Medium Industry Growth	High Industry Growth
Agriculture	15.3	10.0	10.0	6.8
Industry	21.4	27.0	30.0	34.5
Services	63.3	63.0	60.0	58.7

Table 2: Alternative sectoral composition pathways by 2047 (per cent share of GDP)

Year	Agriculture	Industry	Services
2022	15	21	63
2047	10	30	60
2070	10	30	60

Table 3: Assumed sectoral distribution of GDP over time (per cent share)

Sectoral Electricity Demand Projection

Sectoral electricity demand is estimated by linking electricity sales to sectoral economic output using historical data from 2012 to 2022[3]. The estimation draws on sectoral GVA data from the Reserve Bank of India[4] and sector-wise electricity sales from the Central Electricity Authority. A one-year lag structure is employed to reflect the possibility that electricity demand responds to economic activity

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[3] The regression was estimated over a ten-year historical period, balancing the need for statistical reliability with the importance of reflecting more recent changes in India's economic structure.

[4] Sectoral GVA is grouped into three broad categories. Agriculture encompasses agriculture, forestry, and fishing. Industry covers mining and quarrying, manufacturing, and electricity, gas, water supply, and other utility services. Services includes construction, trade, repair, hotels and restaurants, transport, storage, communication and broadcasting-related services, and financial, real estate, and professional services. Public administration, defence, and other services form a separate category and are outside the scope of this study.

with some delay, and to reduce concerns around reverse causality (Wooldridge, 2010). The resulting relationships are used to project electricity demand under alternative sectoral growth paths.

Sector	Coefficient	Intercept
Agriculture	0.12	21,633.9
Industry	0.16	70,726.9
Services	0.06	19,267.2

Table 4: Estimated relationship between sectoral output and electricity demand

The estimated coefficients reflect broad differences in electricity intensity across sectors. Industry exhibits the strongest responsiveness to output growth, consistent with its electricity-intensive character. Agriculture shows moderate responsiveness, reflecting mechanisation and irrigation use, while services exhibit comparatively lower average electricity intensity.

Incorporating Demand-side Efficiency Gains

Projected electricity demand is adjusted downward to account for improvements in electricity efficiency over time, arising from technological change, more efficient equipment and appliances, improved industrial processes, and structural shifts in economic activity. The following uniform adjustments are applied across sectors:

- 5 per cent reduction by 2047 (derived conservatively from historical trends)[5]
- 15 per cent reduction by 2070

A more disaggregated treatment of sector-specific efficiency gains would require additional assumptions that are difficult to justify consistently over such a long time horizon.

From Final Demand to Gross Generation Requirements

The demand projections represent final electricity sales. To estimate the level of electricity that must be generated to meet this demand, the analysis incorporates transmission and distribution losses along with auxiliary Consumption within power plants.

Year	Auxiliary Consumption (%)	T&D Loss (%)
2022	5.80	15.80
2047	5.00	10.00
2070	4.50	6.00

Table 5: Assumptions on system losses and auxiliary Consumption

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[5] Calculated by the author using data sourced from the Ministry of Statistics and Programme Implementation, Energy Statistics India 2025.

These assumptions reflect gradual improvements in network performance and plant operation over time, while recognising that some degree of losses and auxiliary Consumption is likely to persist across the analysis horizon.

Allocation of Generation Across Sources

Gross electricity generation is allocated across three broad source categories: steam (coal-based generation); renewable energy sources (solar, wind, bio-power, and small hydro); and others (nuclear, large hydro, gas, and diesel). Multiple generation-mix scenarios are used to examine how different pathways affect long-term capacity, fuel use, and emissions.

Scenario	Steam (%)	RES (%)	Others (%)
Low-RES growth	70	15	15
Conservative RES growth	65	20	15
Desirable RES growth	35	50	15
Optimistic RES growth	25	60	15

Table 6: Illustrative electricity generation mix scenarios for 2047

Among the 2047 scenarios, the pathway in which renewables account for 50 per cent of total electricity generation is used as the reference basis for extension to 2070, as it is most closely aligned with national planning narratives and comparable long-term assessments.

Scenario	Steam (%)	RES (%)	Others (%)	LEAP Definition
Scenario 1	25	63	12	
Scenario 2	15	73	12	Business-as-Usual
Scenario 3	11	77	12	Low-carbon

Table 7: Electricity generation mix under alternative pathways in 2070

Of the three pathways, Scenarios 2 and 3 are carried forward into the LEAP framework for detailed analysis. Within LEAP, the Business-as-Usual scenario represents continued policy momentum, gradual efficiency improvement, and rising renewable penetration without an accelerated transition away from coal. The Low-carbon scenario represents a more ambitious supply-side transformation, characterised by faster growth in renewable and nuclear energy and a substantially reduced reliance on coal-based generation. Both scenarios are anchored in the same macroeconomic and electricity demand outlook, ensuring that differences in outcomes are attributable to supply-side choices rather than demand-side variation. Across the two scenarios, the only parameters that vary are the generation mix, expressed as shares of steam, renewable energy sources, and others, and the process efficiency assumptions for thermal technologies. All other parameters, including utilisation factors, loss assumptions, disaggregation shares, and emission factors, are held constant across scenarios.

Disaggregation of Renewable Energy and Other Sources

Renewable electricity generation is further distributed across solar, wind, bio-power, and small hydro based on observed shares and expected long-term trends.

Technology	2023 (%)	2070 (%)
Solar	51	68
Wind	37	25
Bio-power	8	4
Small Hydro	4	3

Table 8: Composition of renewable electricity generation

Solar is expected to become increasingly dominant in the renewable mix, reflecting both recent deployment trends and the strong policy emphasis on solar expansion (Singh, 2023; Ministry of Power, 2024). The "others" category is disaggregated as follows.

Technology	2023 (%)	2070 (%)
Large Hydro	63.5	32
Nuclear	17.9	40
Gas	17.5	26
Diesel	0.9	2

Table 9: Composition of other generation sources

Bio-power is further split between biomass and waste-to-energy, as shown below.

Source	2023 (%)	2070 (%)
Biomass	83.8	72
Waste	16.1	28

Table 10: Composition of bio-power generation

Installed Capacity Estimation

Installed capacity is calculated using the standard relationship between generation and utilisation:

$$(1) \qquad C_{i,t} = \frac{G_{i,t}}{8760 \times A_{i,t}}$$

where $i$denotes the generation technology, $t$denotes the yearand $G_{i,t}$is electricity-generating, and$A_{i,t}$is the availability factor, representing the capacity utilisation factor for renewables and the plant load factor for thermal technologies.

Technology	2023 (%)	2070 (%)
Solar	16	26
Wind	21	32
Biomass	16	24
Small Hydro	22	25
Large Hydro	33	35
Nuclear	67	80
Gas	19	25
Diesel	6	5
Waste	54	65
Coal	70	65

Table 11: Assumed utilisation levels across generation technologies

Equation (1) makes an important structural feature of the electricity transition explicit: technologies with lower utilisation factors, such as solar and wind, require substantially larger installed capacity to deliver a given level of generation. A transition towards higher levels of renewable energy, therefore, reduces emissions but simultaneously increases the scale of capacity expansion required.

5. Estimation of Generation

Generation can equivalently be expressed as:

$$(2) \qquad G_{i,t} = C_{i,t} \times 8760 \times A_{i,t}$$

This relationship provides the accounting basis linking capacity projections to generation outcomes and ensures internal consistency within the modelling framework.

6. Estimation of Fuel Requirements

Fuel requirements for thermal generation technologies are estimated as:

$$(3) \qquad F_{i,t} = \frac{G_{i,t}}{\eta_{i,t}}$$

where $\eta_{i,t}$ denotes the process efficiency of technology i in year t, representing the conversion efficiency of fuel energy into electricity.

Technology	2023 (%)	2070 (%)
Coal	36.03	39
Gas	42.5	46
Biomass	22.15	25
Nuclear	33	35
Waste	20.5	23

Table 12: Process efficiency assumptions under Business-as-Usual

Technology	2023 (%)	2070 (%)
Coal	36.03	41
Gas	42.5	48
Biomass	22.15	27
Nuclear	33	36
Waste	20.5	25

Table 13: Process efficiency assumptions under Low-carbon

By linking fuel input directly to generation through Equation (3), the framework captures the moderating effect of efficiency improvements on fuel demand, even where electricity generation continues to rise.

7. Estimation of Emissions

Greenhouse gas emissions are estimated as:

(4) $E_{i,t} = F_{i,t} \times \mathrm{EF}_i \text{where} \quad _i$l is the fuel-specific emission factor for technology i. The analysis includes carbon dioxide, methane, and nitrous oxide, with results expressed in carbon dioxide equivalent terms using 100-year global warming potentials.

GHG	Coal	Gas	Waste
CO_2	90.6 g/MJ	49.4 g/MJ	91.7 g/MJ
CH_4	1 kg/TJ	1 kg/TJ	30 kg/TJ
N_2O	1.5 kg/TJ	0.1 kg/TJ	4 kg/TJ

Table 14: Emission factors used for major fuels

Emission factors are based on the CEA CO_2 database and the 2006 IPCC Guidelines. Emissions are estimated on a point-of-combustion basis. Solar, wind, hydro, and nuclear are accordingly treated as having zero direct combustion emissions. Biomass is treated as carbon-neutral at the point of combustion, in line with standard energy accounting conventions.

8. Key Assumptions

A set of interrelated assumptions concerning the generation mix under each scenario, the composition of aggregated source categories, technology-specific utilisation parameters, process efficiency improvements, and fuel-specific emission factors drives the electricity supply module. These assumptions draw on a combination of historical data, observed trends, published sources, and forward-looking judgment regarding technology development and policy direction.

9. Rationale for the Modelling Approach

The analytical framework adopted here is designed to balance rigour, transparency, and practical usability. A fully optimisation-based model would require detailed assumptions on costs, plant-level dispatch, temporal balancing, and system constraints. While such models are valuable for specific planning applications, they are not necessary for the present purpose.

The objective is to understand how alternative generation pathways affect broad system outcomes over the long term. The system-level accounting approach is well-suited to this purpose because it makes the relationships between demand, generation, capacity, fuel use, and emissions explicit and traceable, and allows the implications of supply-side choices to be interpreted clearly and consistently across scenarios.

Results

Electricity Generation

Total electricity generation is projected to increase substantially over the analysis period, rising from 1,939 TWh in 2023-24 to approximately 25,481 TWh under the BAU scenario and 25,475 TWh under the Low-carbon scenario by 2070, representing a nearly thirteen-fold increase over the base year (Figure 2). As expected, the total generation trajectory is virtually identical across the two scenarios, reflecting the fact that both are anchored in the same macroeconomic and demand outlook. The marginal difference in terminal-year generation arises from slightly different generation-mix assumptions across the two scenarios, with the Low-carbon scenario's higher renewable share requiring a marginally different gross generation to meet the same final electricity demand.

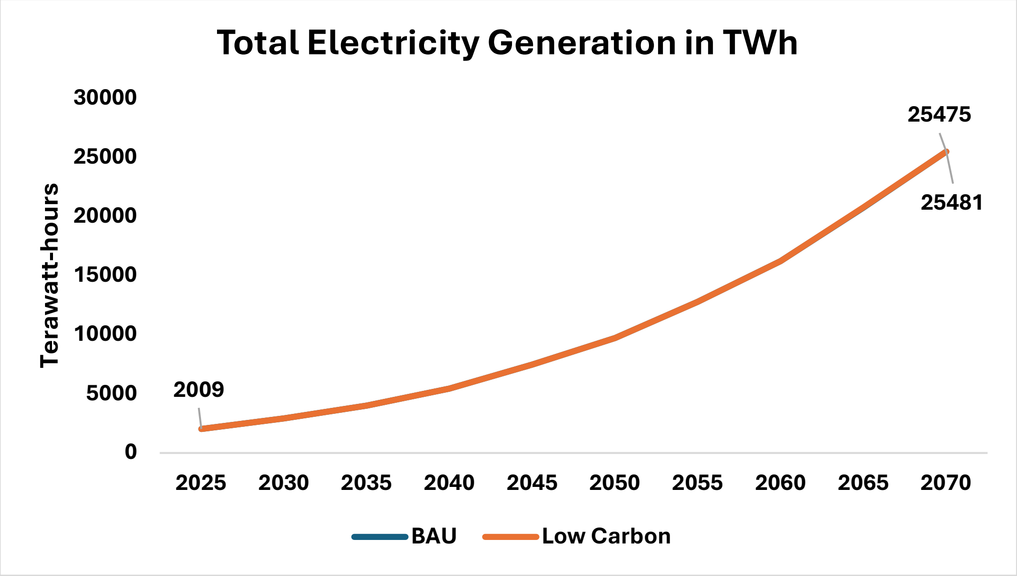

Figure 43: Total Electricity Generation in TWh (2025-2070): BAU and Low-carbon Scenarios

The source-wise breakdown, however, reveals meaningful structural divergence between the two scenarios (Figures 3 and 4). Under the BAU scenario, coal continues to account for a significant share of total generation throughout the projection period. At the same time, solar and wind expand steadily, with coal remaining the dominant source in absolute terms by 2070. Under the Low-carbon scenario, the composition shifts more decisively, with solar emerging as the dominant source of generation and coal's absolute contribution declining relative to the BAU pathway. In both scenarios, solar constitutes the fastest-growing generation source, consistent with the assumed increase in its share within the renewable mix from 51 per cent in 2023 to 68 per cent by 2070.

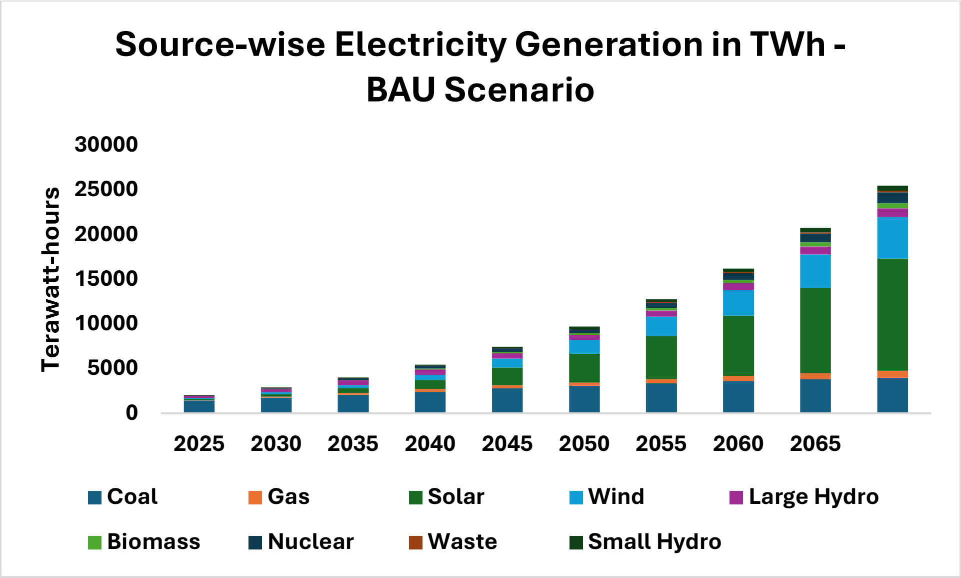

Figure 44: Source-wise Electricity Generation in TWh, BAU Scenario (2025-2070)

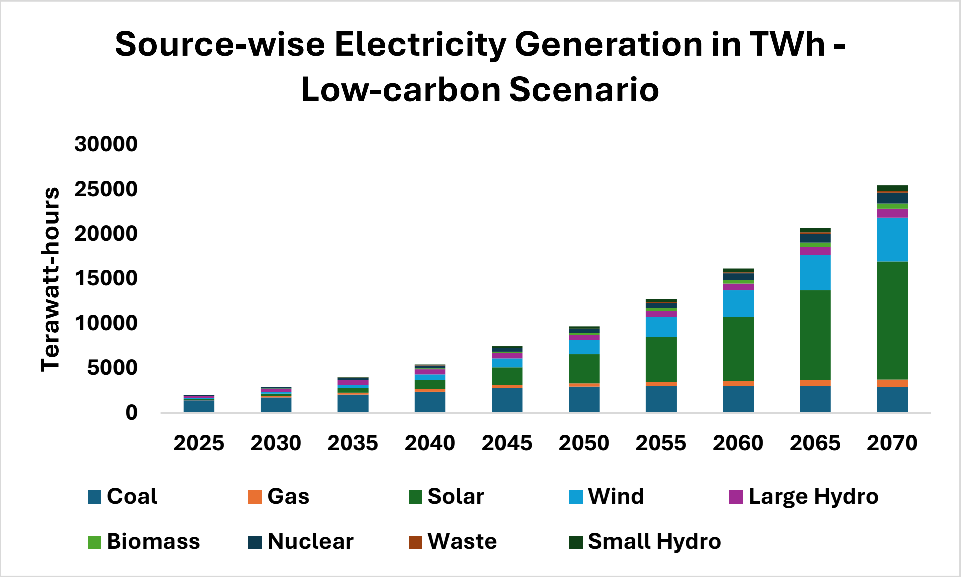

Figure 45: Source-wise Electricity Generation in TWh, Low-carbon Scenario (2025-2070)

Installed Capacity

Total installed capacity is projected to grow from 481,475 MW in 2023-24 to approximately 9,274,740 MW under the BAU scenario and 9,522,238 MW under the Low-carbon scenario by 2070, representing increases of roughly nineteen-fold and twentyfold, respectively, over the base year (Figure 5). The higher terminal capacity requirement under the Low-carbon scenario reflects the structural consequence of a generation mix weighted more heavily towards renewable sources, which carry lower utilisation factors than thermal technologies and therefore require greater installed capacity to deliver equivalent generation volumes.

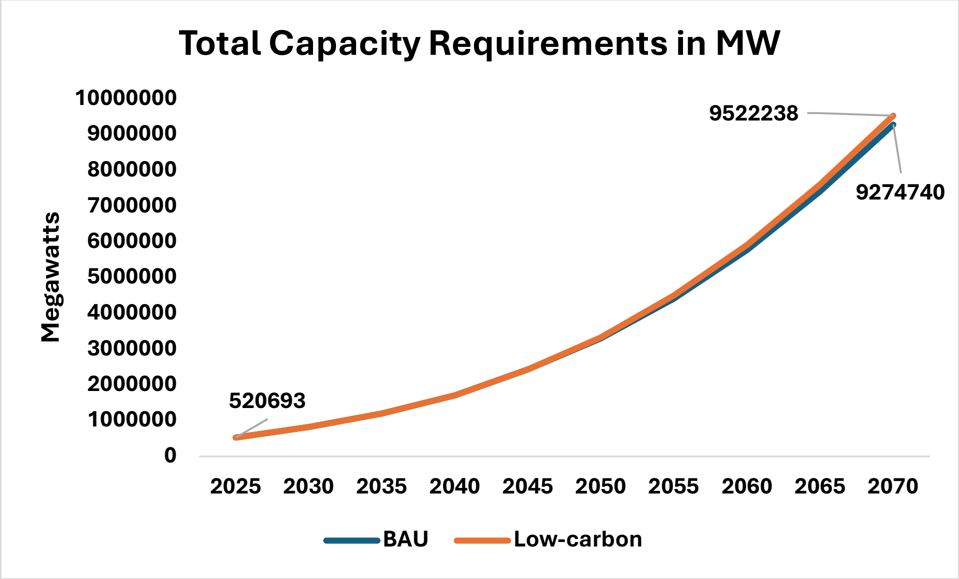

Figure 46: Total Installed Capacity Requirements in MW (2025-2070): BAU and Low-carbon Scenarios

The source-wise capacity charts (Figures 6 and 7) clearly illustrate this dynamic. Solar dominates the capacity expansion in both scenarios, driven by its combination of rapidly growing generation share and relatively low capacity utilisation. The contribution of coal to total installed capacity declines relative to total capacity across both scenarios, though the decline is more pronounced under the Low-carbon pathway. Nuclear capacity grows substantially by 2070, particularly under the Low-carbon scenario, reflecting its assumed increasing share within the other category.

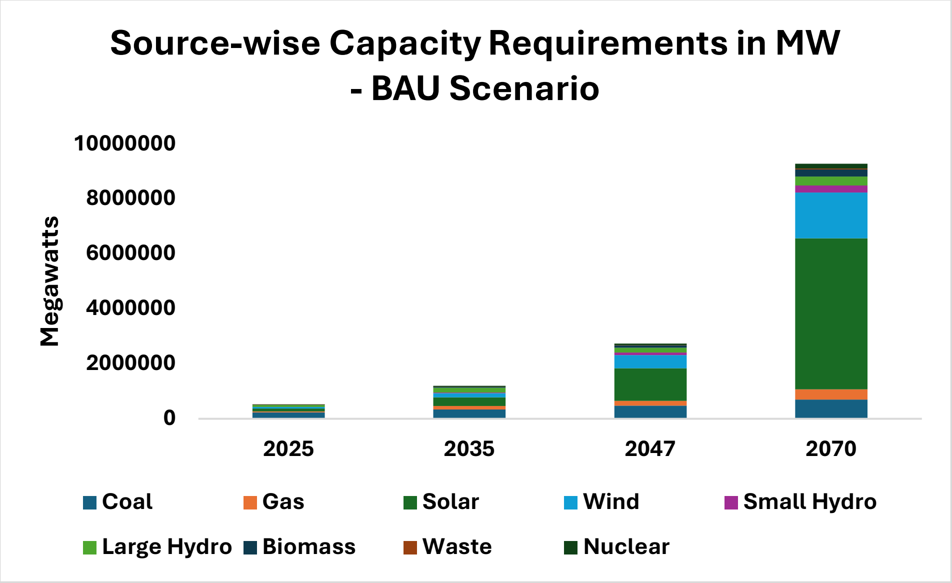

Figure 47: Source-wise Capacity Requirements in MW, BAU Scenario (2025, 2035, 2047, 2070)

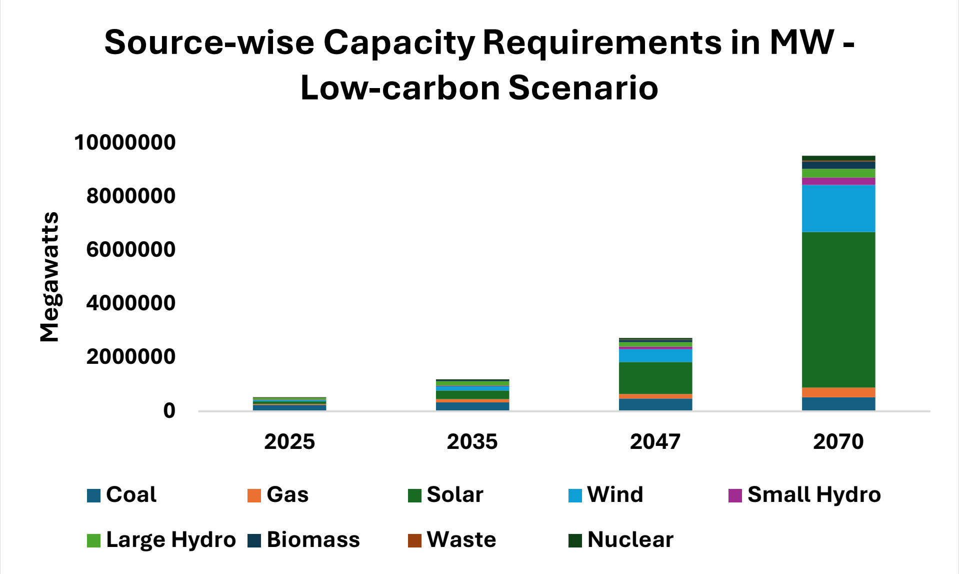

Figure 48: Source-wise Capacity Requirements in MW, Low-carbon Scenario (2025, 2035, 2047, 2070)

Fuel Input

Total fuel input is projected to increase from approximately 17 billion GJ in 2023-24 to 66 billion GJ under the BAU scenario and 55 billion GJ under the Low-carbon scenario by 2070, representing increases of approximately 288 per cent and 224 per cent, respectively, over the base year (Figure 8). Unlike generation, where the two scenarios converge, fuel input diverges meaningfully, with the Low-carbon scenario requiring around 17 per cent less fuel by 2070 than the BAU pathway.

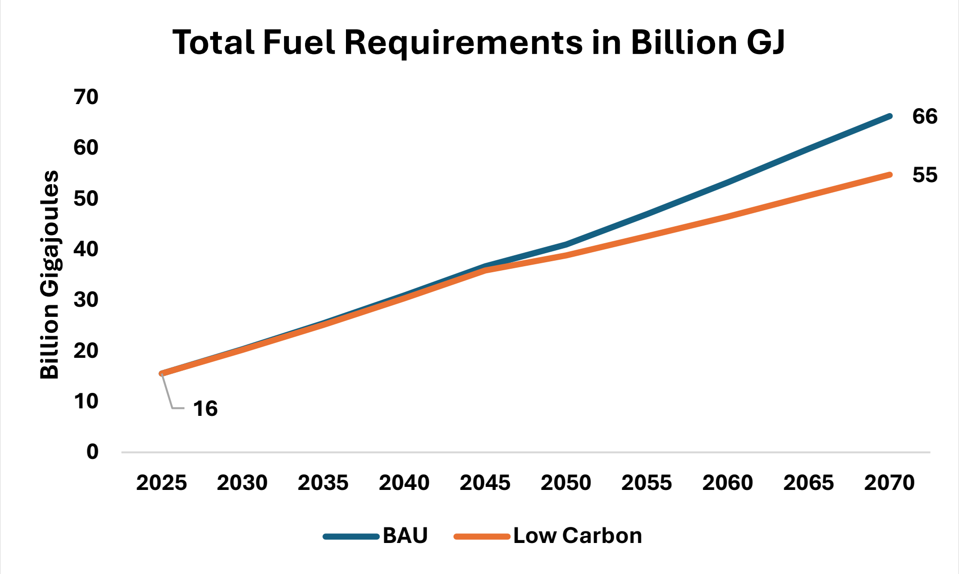

Figure 49: Total Fuel Requirements in Billion GJ (2025-2070): BAU and Low-carbon Scenarios

The source-wise breakdown (Figures 9 and 10) underscores the dominant role of coal in driving fuel requirements under both scenarios. In the BAU scenario, coal fuel input grows continuously throughout the projection period, reaching approximately 36 billion GJ by 2070. In the Low-carbon scenario, coal fuel input peaks around 2045-2050 before declining, ending at a substantially lower level by 2070. Nuclear fuel input grows in both scenarios, becoming an increasingly visible component of the fuel mix, particularly under the Low-carbon pathway. Gas, biomass, and waste together constitute a relatively small share of total fuel requirements throughout the period.

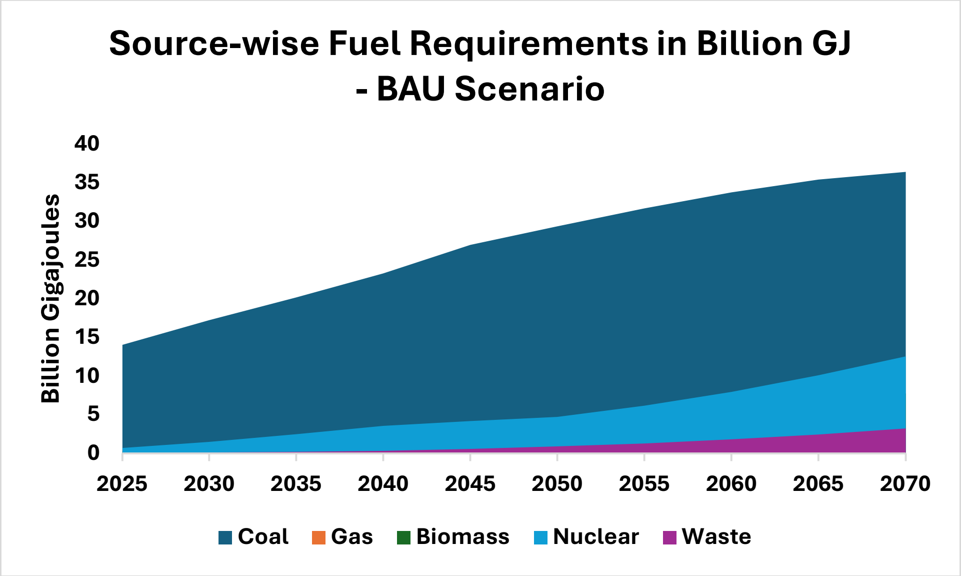

Figure 50: Source-wise Fuel Requirements in Billion GJ, BAU Scenario (2025-2070)

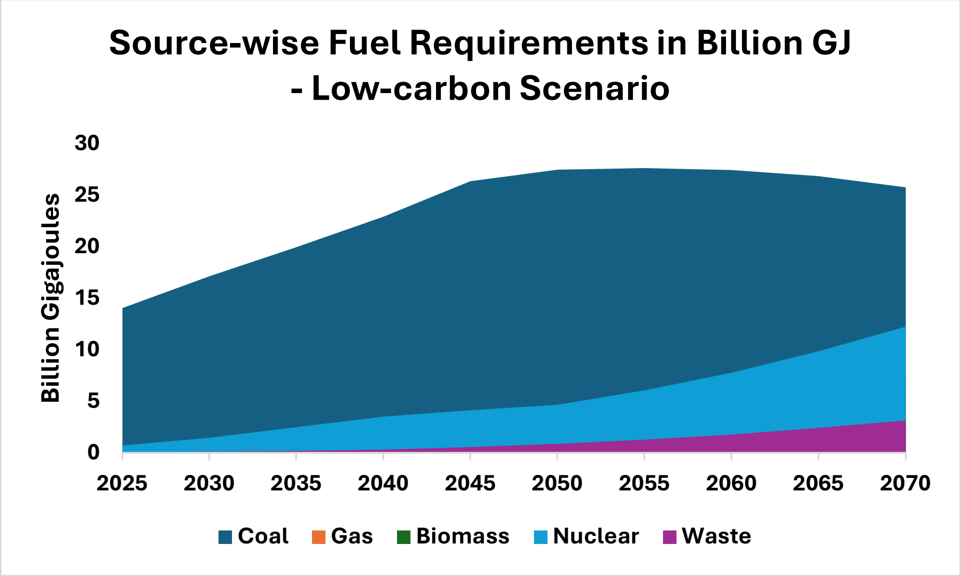

Figure 51: Source-wise Fuel Requirements in Billion GJ, Low-carbon Scenario (2025-2070)

Greenhouse Gas Emissions

Total GHG emissions from electricity generation are projected to rise from 1,371 MTCO2e in 2023-24 to 3,934 MTCO2e under the BAU scenario and 2,939 MTCO2e under the Low-carbon scenario by 2070, representing increases of approximately 187 per cent and 114 per cent r, respectively, over the base year (Figure 11). The two scenarios track closely until approximately 2040, after which the divergence widens progressively, with the Low-carbon scenario emissions plateauing and beginning to moderate in the latter part of the projection period while BAU emissions continue to rise. By 2070, the Low-carbon scenario results in approximately 995 MTCO2e lower annual emissions than the BAU pathway, representing a reduction of roughly 25 per cent.

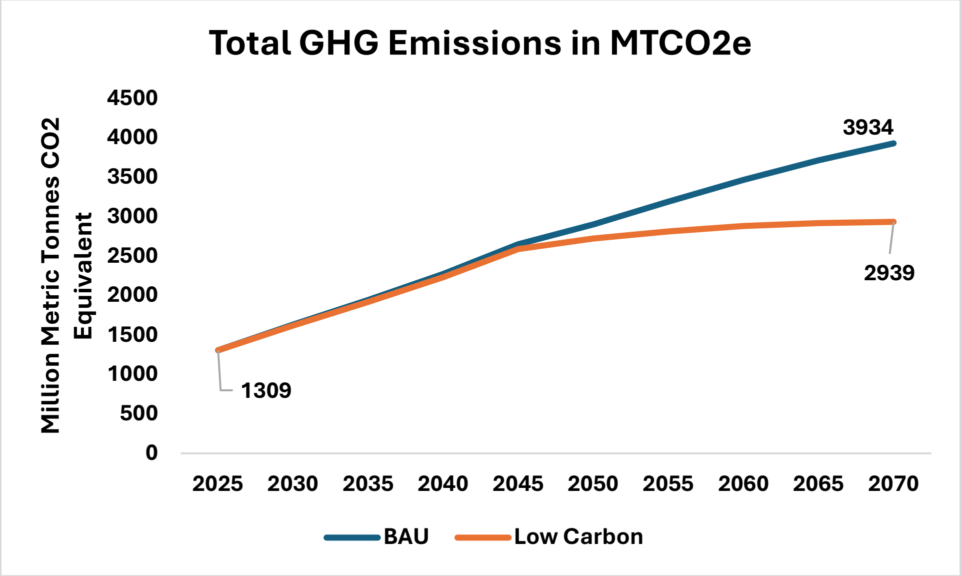

Figure 52: Total GHG Emissions in MTCO2e (2025-2070): BAU and Low-carbon Scenarios

Inferences and Implications

The results provide insights that go beyond the numbers and help explain the broader nature of India's electricity transition.

A key finding is that the choice of generation pathway does not significantly change the amount of electricity India produces, but rather how that electricity is generated. This is important because it shifts how we think about the transition. The discussion is often framed as a trade-off between development and emission mitigation. Still, the results show that electricity demand is mainly driven by economic and social factors, which remain similar across scenarios. What actually changes is the composition of the system, including emissions, fuel use, and infrastructure requirements, not the overall level of electricity supply.

However, this leads to an important implication for emissions. Because electricity demand is growing rapidly, even a cleaner generation mix can still result in rising total emissions for a long period. In other words, the system may become cleaner in structure while still producing more emissions overall. Common indicators, such as the share of renewable energy, may show progress, but total emissions can continue to increase. The results show that emissions rise in both scenarios until the 2040s, after which they diverge. Under the BAU scenario, emissions continue to rise until 2070. This suggests that meaningful reductions in emissions occur only later in the transition and mainly under the Low-carbon pathway.

By 2070, emissions in the Low-carbon scenario are about 25 per cent lower than in BAU, which translates to nearly 1,000 MTCO2e of avoided emissions annually. While this is a large reduction, it is still not sufficient to meet India's net-zero goal, which would require emissions to approach zero. Therefore, the Low-carbon scenario should be seen as an intermediate step rather than an outcome. It reflects the maximum reduction achievable solely through changes in the generation mix and efficiency. Achieving net-zero would require additional measures, such as reducing demand growth, moderating coal use, or adopting technologies like carbon capture, which are not included in this analysis.

Another important finding is the long-term impact of current investment decisions. Both scenarios show that coal continues to play a significant role until at least the 2040s. The amount of coal capacity built in the coming years will influence future emissions in several ways:

- Financially, coal plants entail long-term commitments, such as loans and contracts, that limit investment in cleaner technologies.
- Operationally, systems designed around coal are harder to adapt to renewable energy.
- Politically, coal-related jobs and revenues make it difficult to reduce dependence on coal.

These factors reinforce each other, meaning that decisions made today will affect emissions for decades. Coal plants built now are likely to still operate in the 2050s, shaping long-term emissions trends.

The results also show that the Low-carbon pathway requires a larger total installed capacity than BAU. This means that if renewable energy, storage, and transmission are not developed as assumed, coal will continue to play a larger role than expected, leading to higher emissions. Therefore, achieving the Low-carbon outcomes depends heavily on timely infrastructure development.

The fuel input results further show that emissions reductions come from both a shift in the generation mix and efficiency improvements. These two factors work best when implemented together. However, improving coal efficiency can reduce its operating cost and extend its use, which may slow down the transition away from coal. This means that how and when efficiency improvements are implemented is important.

It is also important to recognise that total emissions do not capture who is affected. Rising emissions over the next few decades will continue to impact air quality, water use, and communities near coal mines and power plants. These impacts are uneven and occur before the benefits of lower emissions are realised.

Overall, the results highlight a key tension in India's energy transition. In the short term, energy security and development require the continued use of coal. In the long term, reducing emissions requires moving away from it. The modelling does not resolve this tension but helps quantify the trade-offs. The central finding is that even ambitious pathways lead to rising emissions for several decades, highlighting the scale of the challenge.

Study Limitations

The analysis adopts a system-level, scenario-based framework that prioritises transparency and internal consistency over granularity. It does not represent plant-level dynamics such as unit-specific retirements or regional variations in infrastructure, and results should therefore be interpreted as system-wide aggregates. Electricity demand is treated as exogenous to the supply module, meaning that interactions between supply conditions and demand behaviour are not captured. The scenario assumptions, including generation mix shares, availability factors, and process efficiencies, reflect well-informed judgements about plausible future trajectories but are necessarily uncertain over a horizon extending to 2070.

6. Policy Recommendations

6.1. Transport Sector

The results show that India's transport energy use and emissions will keep rising till 2050, but the rate of increase can slow down with strong and early action. In the Ambitious case, energy demand is about 13% lower (14.06 EJ), and emissions are about 30% lower (744 million tonnes CO_2e) than the Business-as-Usual case, where the energy demand came out to be 16.16 EJ and emissions came out to be 1,063 million tonnes CO_2e. This means that timely policies, especially those promoting electric vehicles, efficiency, and public transport, can make a clear difference, even if emissions do not start falling yet.

India still has room to shape how its transport system grows. The next decade will decide whether transport demand becomes more efficient and cleaner, or whether the country remains locked into high fossil fuel use and high emissions.

Key Recommendations:

Make public transport and non-motorised transport more attractive

The results indicate that even under the Ambitious scenario, transport energy demand continues to rise, underscoring the need to reduce dependence on private vehicles by enhancing public and non-motorised modes. In Bengaluru, a documented fare elasticity study found that a 10 per cent reduction in bus fares was associated with approximately a 33 per cent increase in bus ridership over five months, highlighting the strong responsiveness of passengers to affordability measures (Urban Mobility India, 2018). In Germany, the three-month €9 monthly ticket experiment in summer 2022 sold over 52 million tickets and was estimated to reduce car traffic and cut about 1.8 million tonnes of CO_2 emissions, demonstrating the potential of low-cost, high-access public transport in shifting mode share (World Economic Forum, 2022). Accordingly, investments in fare-reduction or subsidy schemes, reliable and clean buses and trains, first- and last-mile connectivity, dedicated pedestrian pathways, and safe cycling infrastructure are essential to make public, shared, and non-motorised options more practical and appealing for short and medium-distance trips, thereby reducing reliance on private vehicles. Complementary behavioural strategies, including awareness drives, incentive schemes, and digital nudges, can help influence travel choices toward low-emission modes. When combined with improvements in public transport and infrastructure, these approaches can reduce private vehicle dependence and lower cumulative transport-sector emissions.

Green the Grid

Electrification plays a major role in reducing emissions, but its impact depends on the source of electricity. If EVs are powered by a coal-heavy grid, overall emission benefits remain limited. Studies show that electric trucks charged on India's current power mix emit about 20–35 per cent less greenhouse gases than diesel trucks, and up to 85–90 per cent less when powered by renewables (ICCT, 2024). Therefore, India must continue to green its power mix by adding renewable energy capacity and improving grid flexibility. This ensures that EVs, once scaled up, actually deliver deep emission cuts and contribute to transport sector emissions reduction goals.

Build charging infrastructure and continue targeted subsidies

The expansion of EVs requires reliable and visible charging infrastructure. The International Energy Agency notes that expanding public charging networks and improving their interoperability are key to enabling more widespread and equitable EV adoption (IEA, 2024). India needs to scale up both public charging stations and battery-swapping facilities in urban areas, along highways, and near freight corridors. Continued subsidies and fiscal incentives will help reduce upfront costs for consumers and encourage fleet electrification in public transport and logistics. Public-private partnerships can play a key role in expanding this infrastructure quickly and efficiently.

Focus on freight electrification

Heavy-duty freight trucks are among the hardest sources of transport emissions to reduce. In India, heavy trucks account for more than 40 per cent of on-road fuel consumption and CO_2 emissions, despite representing only about 2 per cent of the vehicle stock (ICCT, 2023). Pilot implementations and early industry trials suggest that India is beginning to lay the groundwork for large-scale freight electrification. Building on these initial efforts through dedicated zero-emission freight corridors, integration with logistics hubs, and renewable-powered charging and refuelling infrastructure will be essential to enable widespread deployment in the coming decades.

Set EV adoption targets for each vehicle segment

While India's EV30@30 target sets an overall direction for electric mobility, it remains too broad to track actual progress on the ground. Different vehicle types are growing at very different rates, so having specific EV targets for each segment, two-wheelers, cars, buses, and freight vehicles, would make progress easier to monitor and manage. Clear segment-wise targets would help identify where adoption is lagging, where policy support needs to be strengthened, and how resources can be better directed to meet the overall national goal.

6.2. Industry Sector

The modelling work done for the select industries provides a clear structural message for India's industrial transition towards Viksit Bharat 2047 and Net Zero 2070. The future of energy demand in hard-to-abate sectors like iron and steel, cement and aluminium will not be determined by marginal efficiency gains alone, but by deliberate shifts in production and technological process pathways, material composition, and circularity. The policy challenge, therefore, is not incremental optimisation but managed structural transformation with a developmental outcome in the backdrop of Viksit Bharat and India's Net Zero goals.

Reorienting Industrial Strategy from Efficiency to Structural Change

Across iron and steel, cement, and aluminium, incremental improvements within incumbent technologies yield only modest change in long-term energy demand. What fundamentally alters trajectories is a change in production mix and technological change. This implies that policy instruments must move beyond traditional energy efficiency frameworks and actively shape technology adoption and material flows by thinking of leapfrogging technologies for the industrial transformation for Viksit Bharat 2047 and Net Zero 2070.

Industrial policy must explicitly support transition technologies that are currently cost-intensive but are also critical for the energy and social system of India. In steel, this means enabling hydrogen-based direct reduction and accelerating the expansion of scrap-based electric arc furnaces by emphasising the circular economy imperatives. In cement, the priority lies in structurally lowering clinker intensity through blended cement standards and material substitution. In aluminium, the dominant lever is a rapid scale-up of secondary production supported by a robust recycling ecosystem.

The implication is clear. Energy transition in industry must be embedded within broader industrial, economic, environmental and development goals, not as a peripheral environmental objective for long-term climate goals.

Creating Enabling Markets for Low-Carbon Materials

A recurring barrier across sectors is the absence of strong demand signals for low-carbon alternatives. Without assured markets, market-based incentives, private investment in hydrogen steel, low-clinker cement, or recycled aluminium will remain cautious.

Public procurement can play a catalytic role. Government-funded infrastructure projects can incorporate embodied carbon disclosure and preferential sourcing requirements. Over time, such measures can evolve into performance-based standards that reward lower carbon intensity rather than prescribing specific technologies. This has to be incentivised with sustained government support and public – private partnerships. Complementary measures such as green product certification, voluntary disclosure frameworks, and alignment with emerging global carbon border mechanisms and market creation must therefore be viewed as a central policy pillar rather than a supplementary measure.

Aligning Energy Infrastructure with Industrial Transition

Energy infrastructure and industrial transition by aligning hydrogen production, transport infrastructure and its clustering, alignment with steel clusters needs to be implemented through coordinated planning between renewable energy expansion, grid infrastructure development, and industrial cluster strategy. Dedicated renewable corridors for industrial hubs, streamlined access to long-term power purchase agreements, and support for captive renewable systems will be essential.

Mobilising Finance for First Movers

Low-carbon industrial technologies are capital-intensive and face cost uncertainties during early deployment stages. Without financial de-risking instruments, private actors may delay investment decisions. This needs to be done through blended financing frameworks and execution structures. Carbon pricing needs to be legitimised for long-term investment signalling.

Strengthening Circular Economy Frameworks

Circularity emerges as a cross-cutting theme, particularly for steel and aluminium. Expanding scrap availability, formalising collection systems, and improving material recovery rates require institutional reforms beyond plant-level interventions by integrating informal recycling networks, establishing digital material tracking systems, and setting recycled content benchmarks in downstream sectors such as construction, automotive, and packaging.

6.3. Agriculture Sector

Implications for Energy Planning and Policy

The results of the agricultural energy demand analysis have important implications for energy planning, infrastructure development, and sector-specific policy design. The magnitude and composition of agricultural energy demand, as well as the sensitivity of demand to technology efficiency, underscore the need for targeted interventions that address the physical drivers of energy use in agriculture rather than relying on aggregate demand management approaches.

Implications for Electricity Planning and Rural Infrastructure

Irrigation pumping emerges as the dominant source of agricultural energy demand, accounting for the majority of electricity consumption in both scenarios. Under the BAU trajectory, agricultural electricity demand increases sharply, driven by rising irrigation requirements and unchanged pump efficiencies. By 2047, electricity demand from irrigation pumping alone will reach close to **18.6 Mtoe**, placing sustained pressure on rural distribution networks. This growth has direct implications for feeder capacity, transformer sizing, and system reliability, particularly during peak irrigation seasons.

The Ambitious scenario demonstrates that efficiency improvements can significantly reduce electricity demand without compromising irrigation services. By 2030, efficiency-driven reductions of over **7 Mtoe** in total agricultural energy demand translate into substantial reductions in electricity load growth. For planners, this highlights that demand-side efficiency in agriculture can act as an effective alternative to costly supply-side investments in rural electricity infrastructure.

Implications for Fuel Demand and Energy Security

Diesel consumption remains a significant component of agricultural energy use, driven primarily by farm mechanisation and diesel-based pump sets. Under BAU, diesel demand increases steadily through the projection period, contributing to higher petroleum product consumption in rural areas. In the Ambitious scenario, improved efficiency reduces diesel demand from both tractors and pumps, leading to cumulative fuel savings.

These reductions have implications beyond the agriculture sector. Lower diesel demand contributes directly to reduced fuel import requirements and enhances energy security. Given that diesel consumption from agriculture is relatively inelastic to short-term price signals, efficiency improvements offer a more reliable pathway for moderating long-term fuel demand growth.

Role of Efficiency as a Planning Instrument

The comparison of scenarios demonstrates that even a uniform **10 per cent improvement in efficiency across agricultural technologies** yields large absolute energy savings. Importantly, these savings are achieved without altering agricultural activity levels, mechanisation intensity, or irrigation requirements. This suggests that efficiency improvements represent a low-risk and high-impact intervention from a planning perspective.

For irrigation pumping, improving pump efficiency reduces electricity consumption directly and also mitigates the impacts of declining groundwater tables on energy demand. For farm mechanisation, improved tractor efficiency lowers diesel consumption per unit of output, moderating the energy implications of rising mechanisation.

Integration with Agricultural and Energy Policy

The results highlight the importance of aligning agricultural policy with energy planning objectives. Policies that promote mechanisation and irrigation expansion must be accompanied by measures that improve equipment efficiency to avoid unintended increases in energy demand. Efficiency-oriented standards, performance-based incentives, and targeted replacement programmes for inefficient pump sets and tractors can play a central role in this regard.

The growing contribution of solar energy in irrigation pumping also has planning implications. While solar pumping reduces grid electricity demand, it does not eliminate the importance of efficiency.

Inefficient solar pump sets can still lead to excessive water extraction and higher system costs. Integrating efficiency criteria into renewable energy deployment programmes is therefore essential.

Implications for Long-Term Demand Management

From a long-term perspective, the results indicate that agricultural energy demand growth is not inevitable. While structural drivers such as mechanisation and irrigation expansion will continue to increase energy requirements, efficiency improvements can substantially moderate this growth. Incorporating explicit efficiency assumptions into energy planning models is therefore critical for producing realistic demand projections.

Overall, the findings suggest that agricultural energy demand should be addressed through a combination of demand-side efficiency measures and coordinated planning across the energy and agriculture sectors. Efficiency improvements in irrigation pumping and farm mechanisation emerge as priority areas for intervention, offering significant energy savings while supporting agricultural productivity and resilience.

6.4. Electricity Supply

Emissions tracking in the power sector should move beyond only reporting capacity or generation shares and explicitly include absolute emissions trajectories.

As renewable energy expands, share-based indicators will increasingly suggest progress even when total emissions continue to rise. Including absolute emissions benchmarks alongside existing metrics would provide a more accurate assessment of the sector's progress toward India's long-term climate goals.

The interaction between thermal efficiency improvements and changes in generation mix should be carefully considered in planning.

Improving the efficiency of coal-based generation reduces emissions per unit of electricity and is an important near-term strategy. However, its full benefits are realised when it is implemented alongside a rising share of renewable energy rather than in isolation. Planning approaches that advance both efficiency improvements and renewable expansion simultaneously are likely to yield better emissions outcomes.

Renewable energy planning should more explicitly account for the broader infrastructure requirements of a system with high renewable penetration.

Compared to a thermal-dominated system, a renewable-heavy system requires significantly higher installed capacity, as well as expanded transmission networks, storage systems, and grid balancing capabilities. Incorporating these requirements early in planning processes can reduce the risk of infrastructure gaps that may slow down renewable deployment or limit system integration.

The timelines for deploying clean energy infrastructure should be treated as an important determinant of emissions outcomes.

Delays or shortfalls in renewable capacity addition, transmission expansion, or storage deployment can extend the role of coal in the generation mix beyond what is assumed in transition scenarios. Explicitly tracking these linkages within monitoring frameworks would help identify bottlenecks and support more targeted policy and investment responses.

The long economic lifetime of coal-based assets should be incorporated into long-term emissions planning.

Coal infrastructure built in the current decade is likely to remain operational into the 2050s. Considering the cumulative emissions associated with these assets, alongside their short-term cost and reliability benefits, would enable more balanced, forward-looking investment decisions better aligned with India's long-term climate commitments.

7. Conclusion

The transition toward Viksit Bharat 2047 and Net Zero 2070 requires a fundamental shift from incremental efficiency improvements to a comprehensive structural transformation across all critical sectors. This analysis demonstrates that while energy demand will inevitably rise to meet developmental goals, the trajectory of this growth can be significantly altered through targeted technological and policy interventions.

The pathway to a low-carbon economy is defined by distinct strategies tailored to the unique energy profiles of each sector:

- **Agriculture**: Decoupling through Equipment Performance. The evolution of energy demand in agriculture is tied to irrigation and mechanisation. Implementing a 10% efficiency improvement across irrigation pump sets and tractors serves as a low-risk, high-impact instrument. This strategy allows the sector to sustain high productivity and output while significantly moderating the pressure on rural electricity infrastructure and reducing diesel consumption.
- **Industry**: Managed Structural Transformation. For hard-to-abate sectors, marginal efficiency gains within incumbent technologies are insufficient.

  In **Iron and Steel**, a shift toward hydrogen-based DRI and scrap-based EAF production can reduce energy demand by 37% relative to the baseline by 2047.

  In **Cement**, the primary lever is a structural reduction in clinker intensity through the adoption of blended cements.

  In **Aluminium**, energy demand is shaped by the production mix, where a rapid scale-up of secondary production and a robust recycling ecosystem can reduce demand by 33% by 2047.

- **Transport**: Modal Shifts and Freight Electrification. While transport emissions will continue to rise through 2050, the rate of increase can be curbed by making public and non-motorised transport more attractive through fare affordability and infrastructure quality. Furthermore, greening the grid is essential to ensure that the electrification of passenger vehicles and heavy-duty freight trucks delivers deep emission cuts rather than shifting the carbon burden to the power sector.
- **Electricity Supply**: Beyond Share-Based Indicators. The power sector's transition is a shift in composition rather than a change in the overall volume of electricity supplied. While renewable energy capacity is a key metric, planning must move toward tracking absolute emissions trajectories. Decisions made in the current decade regarding coal-based assets will have 40-year implications; therefore, aligning thermal efficiency with rapid renewable expansion and infrastructure readiness (storage and transmission) is critical to avoid long-term carbon lock-in.

The findings of this report underscore that India's energy future is not a trade-off between development and emission mitigation. Instead, it is a challenge of strategic alignment. By integrating circular economy frameworks, such as formalising scrap collection and setting recycled content benchmarks with market-creating policies like public procurement of low-carbon materials, India can catalyse a new generation of production systems.

Ultimately, the transition depends on the speed of infrastructure deployment and the mobilisation of finance for first-mover technologies. By prioritising these sector-specific transformations today, India can decouple its economic growth from energy-intensive pathways, ensuring a resilient, secure, and sustainable trajectory toward its mid-century and the 2070 goal.

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9. Appendix

Overview of the LEAP Platform

For this study, the Low Emissions Analysis Platform (LEAP), formerly Long-range Energy Alternatives Planning, was utilised. It is widely used for integrated resource planning, greenhouse gas (GHG) mitigation, and Low Emission Development Strategies (LEDS), especially in developing countries. Many countries rely on LEAP for reporting to the United Nations Framework Convention on Climate Change (UNFCCC) (Stockholm Environment Institute, 2025). LEAP models the impact of structural economic changes and policy interventions on energy demand, but it does not model the feedback effects of changes in energy demand on the economy. We utilised the LEAP platform to develop an in-house energy model in ACPET, called the **LEAP-ACPET model**, which can be scaled for applications ranging from cities and states to national, regional, and global levels.

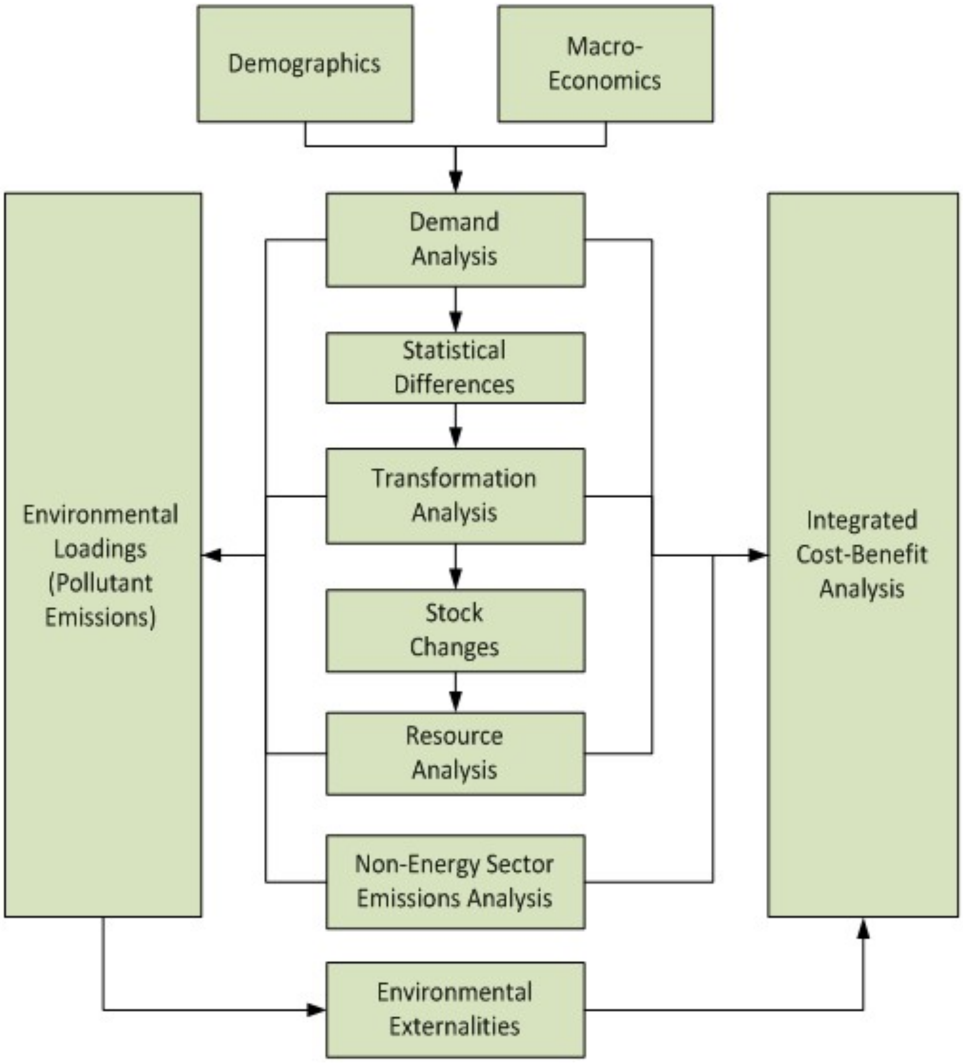

Figure A.1: The Structure of LEAP's Calculations

Transport - Model Configuration and Data Inputs

All base-year (2019–20) data are entered into LEAP under the Current Accounts scenario. This scenario defines the initial conditions of the model and represents historical or observed data. Emission factors are also entered exogenously in the Current Accounts and remain constant across all subsequent scenarios to ensure comparability of results.

The total transport demand for the projection period 2020–21 to 2049–50 is estimated externally (outside LEAP) and then input as an exogenous variable in all scenarios following Current Accounts. This projected total demand is disaggregated into passenger and freight components according to their percentage shares in the overall transport activity, derived from the aggregation of billion passenger-kilometres (BPKM) and billion tonne-kilometres (BTKM) projections. The total transport demand projections and passenger and freight shares remain constant across all scenarios to maintain a consistent activity base.

In the subsequent scenarios, parameters including modal shares (passenger and freight), vehicle category distributions within road transport (passenger and freight), technology composition within categories under all modes (passenger and freight), and final energy intensities or fuel efficiencies are derived by modifying the base-year values established in Current Accounts according to the scenario-specific assumptions defined in this study.

a. Representation of Vehicle Categories

Within the model, the category “Cars” is treated as representative of cars, jeeps, and vans, while “Buses” includes omnibuses under the same classification. This aggregation ensures data consistency across available statistical sources while preserving the distinct energy-use characteristics of each vehicle class.

b. Key Assumptions

1. Vehicle Life (years)

Road Vehicle Category	Assumption
Car	15
Taxis	12
Buses	15
Two wheelers	15
Three wheelers	15
Heavy Commercial Vehicles	15
Light Commercial Vehicles	15

Table A1: Vehicle Life Assumptions

2. Annual Distance Travelled (km)

Road Vehicle Category	**Assumption**
Car	11560
Taxis	70000
Buses	73000
Two wheelers	6300
Three wheelers	27900
Heavy Commercial Vehicles	60000
Light Commercial Vehicles	25000

Table A2: Annual Distance Travelled Assumptions

3. Occupancy

Road Vehicle Category	**Assumption**
Car	2.5
Taxis	2.8
Buses	35
Two wheelers	1.5
Three wheelers	2.38

Table A3: Occupancy Assumptions

4. Payload/ Load factor

Road Vehicle Category	**Assumption (tonnes)**
Heavy Commercial Vehicles	11
Light Commercial Vehicles	1.8

Table A4: Payload Assumptions

Sources: S.K. Singh (2006), NITI Aayog and Rocky Mountain Institute. (2017b), Voluntary Vehicle Fleet Modernization Program (V-VMP)/ Vehicle Scrapping Policy, Rue du Can et al. (2009), Vehicle Scrappage Policy, CSTEP, CEEW, IRADe, PNNL, and TERI (2019), & Arora, Vyas, and Johnson (2011), T.V. Ramachandra, Shvetmala (2009).

5. Vehicle Mileage (distance per unit of fuel)

Mode – Category - Fuel	**Assumption**
Road – Cars - CNG	17.44 km/kg
Road – Cars - Diesel	14.9 km/l
Road – Cars - FCV	2.93 km/kWh
Road – Cars - Petrol	15.8 km/l
Road – Cars – Electric	31.5 km/kWh
Road – Taxis - CNG	17.44 km/kg
Road – Taxis - Diesel	14.9 km/l

Road – Taxis - Electric	9.48 km/kWh
Road – Buses - CNG	2.26 km/kg
Road – Buses - Diesel	4.5 km/l
Road – Buses - FCV	0.29 km/kWh
Road – Buses – Electric	0.8 km/kWh
Road – 2W - Petrol	57.4 km/l
Road – 2W - Electric	50 km/kWh
Road – 3W - CNG	24.1 km/kg
Road – 3W – Diesel	37.9 km/l
Road – 3W - Petrol	35.5 km/l
Road – 3W - Electric	15.4 km/kWh
Road - HCV - CNG	9.5 km/kg
Road – HCV - Diesel	6 km/l
Road – HCV - FCV	0.38 km/kWh
Road – LCV -CNG	18 km/kg
Road – LCV - Diesel	15 km/l
Road – LCV - FCV	3.5 km/kWh
Rail – Passenger - Diesel	0.26 km/l
Rail – Passenger - Electric	0.05 km/kWh
Air – Passenger - ATF	0.21 km/l

Table A5: Vehicle Mileage Assumptions

6. Vehicle Fuel Efficiency (fuel per unit of distance)

Mode – Category - Fuel	**Assumption**
Road – HCV - Electric	0.1853 kWh/km
Road – LCV - Electric	0.2834 kWh/km
Rail – Freight - Diesel	0.0049 l/km
Rail – Freight - Electric	0.0200 kWh/km
Air – Freight - ATF	0.2752 l/km

Table A6: Vehicle Fuel Efficiency Assumptions

Sources: NITI Aayog and Rocky Mountain Institute. (2017a), Goel et al. (2016), MoRTH (2017), CEEW - India's Electric Vehicle Transition (2020), ICCT (2020), TERI's ROADMAP FOR INDIA'S ENERGY TRANSITION IN THE TRANSPORT SECTOR (2024), & IESS 2047 Version 3.

c. Key Data Sources

3. **Data**	**Source**
GDP (2000 to 2025)	Database on Indian Economy - Macroeconomic Aggregates (Constant prices)
GDP (2026 to 2050)	IESS 2047 Version 3
Population (2000 to 2024)	Database on Indian Economy - Macroeconomic Aggregates (Current Prices)
Population (2025 to 2050)	IESS 2047 Version 3: United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019
GHG Emission Factors	GHG Protocol (World Resources Institute / World Business Council for Sustainable Development)

Table A7: Key Data Sources

a. Detailed Scenario Assumptions

1. Business as Usual Scenario (BAU)

Lever	**2050 Assumption**	**Rationale**
	Passenger Transport Demand	
Modal shift	Road: 84%	Road transport continues to dominate passenger mobility due to its extensive connectivity, flexibility, and convenience for both intra- and inter-city travel. Despite improvements in rail and air services, road-based passenger activity remains high as urbanisation, income growth, and private vehicle ownership expand.

	Rail: 13%	Railways' share remains stable, supported by ongoing modernisation and capacity enhancement through projects such as the Vande Bharat and Amrit Bharat trains. The commissioning of Dedicated Freight Corridors (DFCs) further frees up passenger line capacity, improving reliability and speed.
	Air: 3%	The share of air travel marginally rises owing to increasing disposable incomes and improved connectivity under the UDAN (Ude Desh ka Aam Nagrik) Regional Connectivity Scheme, which has expanded operational airports and routes across Tier-2 and Tier-3 cities.
	Freight Transport Demand	
	Road: 64.97%	Road freight continues to dominate for short- and medium-haul deliveries. The sector benefits from improved highways and initiatives such as the Bharatmala programme and the growing logistics industry.
	Rail: 35%	The share of rail freight increases significantly, driven by the implementation of the National Rail Plan (NRP), which targets raising rail's freight share to 45% by 2030 through the DFC network and multimodal logistics parks.
	Air: 0.03%	Air freight remains a niche segment, primarily for high-value and perishable commodities, given the high cost of air logistics and limited infrastructure.
Shift in shares of vehicle categories in Road Transport	Passenger Road Transport Demand	

	Cars: 25%	Rising incomes, urban sprawl, and aspirational ownership continue to drive car demand. Private vehicle ownership remains a symbol of mobility and comfort despite growing mass transit availability.
	Taxis: 10%	Growth in app-based taxi aggregators sustains demand for on-demand, point-to-point mobility, particularly among younger urban users who prioritise convenience over ownership.
	2W: 28%	Two-wheelers remain the most affordable and flexible mobility mode, widely used for commuting and last-mile connectivity. Urban delivery and logistics services further sustain this segment.
	3W: 6%	The share of 3-wheelers slightly declines as app-based taxi services and affordable 2W taxis gain prominence, offering better comfort and transparent pricing.
	Buses: 31%	Bus usage remains significant but declines due to competition from private modes and metro expansion. Nevertheless, programs such as PM e-Bus Sewa continue to strengthen bus-based public transport.
	Freight Road Transport Demand	
	LCV: 30%	The share of Light Commercial Vehicles (LCVs) increases as e-commerce and last-mile delivery services expand. LCVs are cost-effective for small-load, short-haul movement and benefit from the rise in intra-city logistics.
	HCV: 70%	Heavy Commercial Vehicles (HCVs) continue to dominate bulk and long-haul freight but experience a marginal decline in share as some bulk

		movement shifts to rail following DFC operationalisation.
Share of electric vehicles/ electricity as a technology	Passenger	
	Cars: 15%	Electric car adoption progresses with continued incentives under FAME-II and successor programs, along with declining battery costs. However, limited charging infrastructure and high upfront prices constrain rapid uptake.
	Taxis: 15%	Electric taxis increase gradually, supported by fleet-level economics and government incentives. Operational challenges such as charging downtime and battery replacement costs moderate the pace.
	2W: 30%	Two-wheeler electrification accelerates under FAME-II and various state EV policies, driven by low total cost of ownership for delivery and commuter segments.
	3W: 50%	Three-wheelers emerge as the fastest-growing EV segment, favoured by short routes, depot charging, and demand incentives under FAME-II.
	Buses: 10%	The share of electric buses rises moderately under PM e-Bus Sewa, though adoption is constrained by upfront costs and infrastructure limitations.
	Rail: 100%	Indian Railways achieves complete electrification in line with its official targets, contributing to lower emissions from rail transport.

	Freight	
	LCV: 10%	Electrification in the freight sector remains limited to LCVs operating in urban and peri-urban areas. The potential for depot charging and short-haul routes enables modest EV penetration.
	HCV: 5%	Adoption of electric HCVs remains constrained due to battery weight, limited fast-charging infrastructure, and higher costs. Demonstration pilots continue, but large-scale uptake is unlikely in BAU.
	Rail: 100%	Rail freight becomes fully electric in line with national electrification targets, enhancing efficiency and reducing diesel dependence.
Share of Hydrogen Fuel Cell Vehicles/ hydrogen as a technology	Passenger	
	Cars	No significant deployment of hydrogen fuel cell passenger vehicles is expected in BAU, as policy and pilot efforts in India are presently focused on heavy-duty and industrial applications. High costs and lack of refuelling infrastructure further limit uptake.
	Buses	While pilot hydrogen buses have been tested in Leh, Gujarat, and Delhi, large-scale deployment remains unviable in BAU due to the cost competitiveness of e-buses and limited hydrogen availability.
	Freight	

	LCV	No adoption of hydrogen LCVs is anticipated due to the absence of dedicated policy frameworks or pilots.
	HCV	For HCVs, isolated demonstrations are underway, but commercial-scale use remains improbable in BAU without supporting refuelling networks.
Annual Fuel Efficiency Improvements	Passenger	
	Cars: -1%	Improvement aligns with the Corporate Average Fuel Efficiency (CAFE) norms notified by BEE and MoRTH. Incremental technology improvements in internal combustion engines and mild hybrids yield moderate efficiency gains.
	Buses: -0.1%	Bus efficiency improves only slightly due to slower fleet turnover and limited technology upgrades in the existing stock.
	2W: -0.1%	Gradual efficiency improvements are assumed through lighter and more efficient vehicle designs.
	3W: -0.1%	Minor gains expected from efficient engines.
	Taxis: -0.1%	Fleet efficiency improves slightly, but large gains are constrained by operational and cost factors.
	Freight	
	LCV: -0.01%	Improvement follows the Constant Speed Fuel Consumption (CSFC) test-based standards under the Heavy-Duty Vehicle Fuel Consumption Framework, with minimal efficiency gains beyond compliance in BAU.
	HCV: -0.01%	Similar to LCVs, fuel efficiency improvements are compliance-driven, with limited room for further gains due to cost and design constraints.

Table A8: BAU Scenario Assumptions

2. Ambitious Scenario

Lever	2050 Assumption	Rationale
Modal shift	Passenger Transport Demand	
	Road: 72%	The share of road transport declines as investments in public transport and rail infrastructure improve intercity and regional connectivity, reducing dependence on private road travel.
	Rail: 25%	The share of rail transport rises due to network electrification, increased frequency of passenger services, and completion of high-speed and regional rail corridors under the National Rail Plan.
	Air: 3%	Air transport maintains its share as improved connectivity through the UDAN scheme is balanced by a modal shift toward rail for medium-distance routes.
	Freight Transport Demand	
	Road: 54.97%	The share of road freight reduces as bulk commodities increasingly shift to rail.
	Rail: 45%	The share of rail freight increases in line with the National Rail Plan target of achieving 45% freight movement by rail through DFC expansion and improved logistics integration.
	Air: 0.03%	Air freight remains marginal, primarily catering to high-value and time-sensitive goods, with limited infrastructure expansion.
Shift in shares of vehicle	Passenger Road Transport Demand	

categories in Road Transport	Cars: 20%	The share of private cars declines as public transport systems expand, and shared mobility options become more accessible.
	Taxis: 15%	The share of taxis increases due to the wider adoption of app-based on-demand mobility services.
	2W: 23%	The share of two-wheelers declines gradually with improved reliability of public transport options.
	3W: 4%	The share of three-wheelers decreases slightly as taxis and two-wheelers capture a portion of the short-distance mobility market.
	Buses: 38%	The share of buses increases as urban and intercity bus fleets expand under schemes like PM e-Bus Sewa and state-level electric mobility programs, and a policy push for a shift from private to public transport.
	Freight Road Transport Demand	
	LCV: 50%	Light Commercial Vehicles retain a significant share, reflecting growth in e-commerce and last-mile delivery.
	HCV: 50%	Heavy Commercial Vehicles’ share declines relative to BAU as long-haul freight gradually shifts toward rail.
	Passenger	

Share of electric vehicles/ electricity as a technology	Cars: 30%	Electric cars account for a growing portion of private vehicle stock, driven by falling battery prices, expansion of charging networks, and policy continuity through FAME-II and future successor schemes.
	Taxis: 30%	Electric taxis grow steadily due to lower operational costs and targeted fleet incentives in major cities.
	2W: 60%	Two-wheelers achieve high electrification due to declining upfront costs, supportive state EV policies, and demand growth in the delivery and commuting sectors.
	3W: 65%	Electrification of three-wheelers accelerates because of depot-based charging, government subsidies, and suitability for short routes.
	Buses: 25%	A quarter of buses become electric through large-scale adoption under PM e-Bus Sewa and targeted state policies.
	Rail: 100%	Railways achieve full electrification as per the Ministry of Railways targets, contributing to reduced transport emissions.
	Freight	
	LCV: 30%	The share of electric light commercial vehicles increases through fleet electrification in logistics.
	HCV: 15%	Electric heavy commercial vehicles remain a niche but growing segment as battery performance and corridor charging infrastructure improve.

	Rail: 100%	Freight rail is entirely powered by electricity, aligned with the Indian Railways electrification strategy.
Share of Hydrogen Fuel Cell Vehicles/ hydrogen as a technology	Passenger	
	Cars: 5%	Slight increase as compared to the BAU scenario.
	Buses: 5%	
	Freight	
	LCV: 5%	Slight increase as compared to the BAU scenario.
	HCV: 5%	
Annual Fuel Efficiency Improvements	Passenger	Same as in the BAU scenario
	Cars: -1%	
	Buses: -0.1%	
	2W: -0.1%	
	3W: -0.1%	
	Taxis: -0.1%	
	Freight	
	LCV: -0.01%	
	HCV: -0.01%	

Table A9: Ambitious Scenario Assumptions

Electricity Supply - Assumption Rationale

Base year values are drawn from official sources, including the Central Electricity Authority and Ministry of Power publications. Projected values for 2047 and 2070 reflect informed analytical judgement consistent with observed trends and national planning discourse. Given the inherent uncertainty in projections over a 50-year horizon, these assumptions should be interpreted as internally consistent inputs to a scenario framework rather than as point forecasts.

Parameter	2022	2047	2070	Rationale for Projected Values
Auxiliary Consumption (%)	5.8	5.0	4.5	Gradual improvement

				due to more efficient thermal plants; auxiliary use cannot fall to zero.
T&D losses (%)	15.8	10.0	6.0	Consistent with the current global average.

Table A10: System Loss and Auxiliary Consumption Assumptions

Technology	**2023 (%)**	**2070 (%)**	**Rationale for 2070 Value**
Solar	16	26	Improvement from better technology, tracking systems, and site selection; still limited by variability.
Wind	21	32	Higher hub heights and potential offshore deployment improve output over time.
Biomass	16	24	Better fuel supply chains and storage improve utilisation.
Small hydro	22	25	Limited improvement because output depends on rainfall and river flows.
Large hydro	33	35	Mostly stable; small gains from refurbishment and better system coordination.
Nuclear	67	80	Moves closer to long-run performance levels seen in mature nuclear fleets, while remaining a conservative assumption for India.

Gas	19	25	Higher utilisation as gas is used more for balancing renewables, subject to fuel availability.
Diesel	6	5	Remains limited to backup use; utilisation declines slightly as grids and storage expand.
Waste-to-energy	54	65	Assumes major improvements in waste segregation and plant design; represents an optimistic case with more stable, higher-quality fuel supply.
Coal	70	65	Coal operates in roughly the same PLF band as today but gradually shifts to a more flexible role in a renewables-rich system.

Table A11: Utilisation Factor Assumptions

Technology	**BAU 2024 (%)**	**BAU 2070 (%)**	**Low-carbon 2024 (%)**	**Low-carbon 2070 (%)**	**Rationale for Projected Values**
Coal	36	39	36	41	Replacement of older plants with more efficient supercritical and ultra-supercritical units; faster transition in the Low-carbon case.

Gas	42.5	46	42.5	48	Gradual deployment of higher-efficiency combined-cycle technologies over time.
Biomass	22	25	22	27	Gradual shift to more advanced combustion and gasification technologies.
Nuclear	33	35	33	36	Small improvements with newer reactor designs operating at slightly higher temperatures.
Waste-to-energy	20.5	23	20.5	25	Better waste quality and improved conversion systems allow convergence towards typical international performance.

Table A12: Process Efficiency Assumptions

Parameter	**2023 (%)**	**2070 (%)**	**Rationale for 2070 Value**
Solar within RES	51	68	Solar expands fastest due to favourable

			costs and strong resource availability.
Wind within RES	37	25	Share declines relative to solar, though total wind generation may still grow.
Bio-power within RES	8	4	Limited by sustainable biomass availability and competing uses.
Small hydro within RES	4	3	Limited additional economically viable potential.
Large hydro within others	63.5	32	Growth constrained; share declines as nuclear, gas, and other sources expand.
Nuclear within others	17.9	40	Expands as a firm, low-carbon source, subject to policy, technology, and investment constraints.
Gas within others	17.5	26	Plays a larger role in balancing renewable variability and providing flexibility.
Biomass within bio-power	83.8	72	Remains dominant within bio-power but declines slightly as waste-to-energy grows.
Waste within bio-power	16.1	28	Increases with better waste management and urbanisation, assuming successful deployment of waste-to-energy.

Table A13: Generation Mix Disaggregation Assumptions

AI-Powered Conversational System for Indian Energy Policy Information Retrieval (Developed out of this Project)[6]

1. Abstract

India's energy sector is governed by a wide range of policies related to renewable energy, electricity generation and distribution, energy efficiency, and climate commitments. Although most of this information is publicly available, it is often difficult for users to locate, interpret, and keep track of updated policy details. Information is scattered across multiple government websites, reports, and news sources, making manual research time-consuming and inefficient. This policy brief presents an AI-powered, ML-based conversational system designed to simplify access to information on the Indian energy policy landscape. The system allows users to ask questions in natural language and receive clear, concise, and up-to-date responses, with wisdom-based learning in an evolutionary framework. Instead of relying only on stored information, the chatbot can retrieve current data from reliable online sources when required. The application is implemented as a web-based system with a simple chat interface. It is intended for students, researchers, journalists, policymakers, and citizens who wish to understand India's energy policies without having to navigate complex documents. The results demonstrate that conversational wisdom-based AI can significantly improve accessibility and comprehension of public policy information.

2. Introduction

2.1. India's Energy Sector: An Evolving Landscape

Energy plays a central role in India's economic growth, social development, and environmental sustainability. As one of the world's fastest-growing economies, India faces the dual challenge of meeting rising energy demand while ensuring affordability, reliability, and environmental responsibility. The country's energy requirements are influenced by factors such as population growth, rapid urbanisation, industrial expansion, and increasing electricity consumption in households and services. Over the past two decades, India has undertaken significant reforms in its energy sector. These reforms aim to diversify energy sources, reduce dependence on imported fossil fuels, improve the efficiency of electricity generation and distribution, and promote cleaner energy sources. Renewable energy has emerged as a key focus area, with large-scale investments in solar, wind, hydro, and bioenergy projects. At the same time, conventional energy sources such as coal continue to play an essential role in ensuring energy security. India's commitment to global climate action has further accelerated changes in the energy sector. International commitments related to emissions reduction and climate resilience have led to the introduction of new policies, targets, and regulatory frameworks. As a result, the energy sector is characterised by continuous policy evolution, frequent announcements, and regular updates to **existing schemes.**

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[6] Authors: Dr Anandajit Goswami and Mr Saptarshi Poddar, ACPET

2.2. Role of Energy Policies in National Development

Energy policies serve as the foundation for planning, investment, and regulation in the energy sector. In India, these policies are formulated and implemented by multiple government bodies at the central and state levels. Ministries, regulatory authorities, and public sector agencies are involved in designing schemes that influence electricity generation, transmission, distribution, pricing, and consumption. Energy policies affect a wide range of stakeholders, including power producers, distribution companies, industries, farmers, households, investors, and policymakers. Decisions related to tariffs, subsidies, renewable energy targets, and infrastructure development have direct economic and social impacts. For example, policies promoting solar energy influence land use, employment, and manufacturing, while power sector reforms affect electricity access and the financial stability of utilities. Given the broad impact of energy policies, access to accurate and timely policy information is essential. Stakeholders need to understand not only what a policy states, but also its objectives, eligibility criteria, implementation status, and expected outcomes. However, this information is often embedded in lengthy documents and technical reports, making it difficult for non-specialists to interpret.

2.3. Complexity and Fragmentation of Policy Information

One of the major challenges in understanding Indian energy policies is the fragmented nature of information sources. Policy-related data is distributed across multiple government websites, press releases, annual reports, regulatory orders, and parliamentary documents. Each platform follows its own structure, terminology, and update schedule. In many cases, a single policy may be explained through multiple documents released at different points in time. Initial policy announcements are followed by guidelines, amendments, clarifications, and progress reports. Tracking all these updates requires significant effort and familiarity with government processes. For students, researchers, and journalists, this complexity often becomes a barrier to effective analysis. Additionally, most official documents are published in formats such as PDF files that are not designed for quick reference or search-based interaction. Users must manually read through long sections to locate relevant information. This problem is further compounded by technical, legal, and administrative language that may not be easily understood by the general public.

2.4. Limitations of Traditional Information Access Methods

Traditional methods of accessing policy information rely heavily on search engines and manual document review. While search engines can locate relevant webpages, they typically provide a list of links rather than direct answers. Users are required to open multiple sources, assess credibility, and synthesise information independently. Government portals, although authoritative, often lack user-friendly navigation and interactive features. Information is organised based on administrative structures rather than user needs. As a result, users may struggle to identify which ministry or department is responsible for a specific policy area. Generic artificial intelligence tools and chatbots offer some assistance, but they often lack specialisation in wisdom-based learning and interpretation of the Indian energy policy. These tools may provide incomplete or outdated information, especially in a domain where policies change frequently. Without access to real-time updates and domain-specific context, such systems may not meet the needs of serious policy researchers or informed citizens.

2.5. Emergence of Conversational AI for Public Information

Recent advancements in artificial intelligence have enabled the development of conversational systems that can interact with users in natural language. These systems allow users to ask questions in a conversational style, reducing the need for precise keywords or technical queries. Conversational AI has been successfully applied across customer support, education, and healthcare. Its application in public policy and governance is a relatively new but promising area. By translating complex information into simple explanations, conversational systems can help bridge the gap between policy formulation and public understanding. In the context of energy policy, conversational AI can assist users in exploring policy objectives, understanding the benefits of schemes, and tracking recent developments. When combined with access to reliable information sources, such systems have the potential to improve transparency and citizen engagement.

2.6. Rationale for an AI-Based Energy Policy Chatbot

The rationale for developing an AI-powered chatbot for Indian energy policy is the need for an accessible, reliable, and up-to-date information platform. Instead of requiring users to navigate multiple websites or interpret lengthy documents, the chatbot provides a single point of interaction. By allowing users to ask questions in plain language, the system lowers the entry barrier for understanding complex policy issues. The chatbot is designed to focus exclusively on Indian energy policies, ensuring that responses remain relevant and context-specific. The inclusion of real-time information retrieval helps address the challenge of rapidly changing policies. This approach supports a wide range of use cases, from academic research and journalism to general public awareness. It also aligns with broader goals of digital governance and transparency by making public information easier to access and understand.

2.7. Target Users and Use Cases

The system is intended for diverse user groups:

- Students and Researchers, who require quick access to policy details for academic work, Journalists and Media Professionals, who need accurate background information for reporting
- Policy Analysts and Practitioners, who track developments in the energy sector
- Industry Professionals, who seek clarity on regulatory and policy frameworks
- General Citizens, who wish to understand government initiatives affecting energy access, costs and the life of a common citizen

Typical use cases include explaining policy schemes, comparing state-level initiatives, summarising recent announcements, and understanding long-term energy targets.

2.8. Contribution of the Study and The Policy Brief

This policy brief contributes to the field of applied artificial intelligence by demonstrating how conversational systems can improve access to public policy information. It shows that AI-based tools do not need to be highly complex to deliver meaningful value. By focusing on usability, relevance, and clarity, the brief highlights the potential of AI to support informed decision-making and public awareness in the energy sector.

3. Literature Review

3.1. Introduction to the Literature Review

The purpose of this literature review is to examine existing research, tools, and approaches related to conversational systems, artificial intelligence for information access, and policy information dissemination. Understanding prior work in these areas helps establish the relevance of the present research showcased in this policy brief and highlights the gap it aims to address. The review of the policy brief focuses on three broad areas. First, it examines the evolution of conversational systems and their role in information retrieval. Second, it explores the use of artificial intelligence for simplifying complex information, particularly in public policy and governance. Third, it reviews existing sources and platforms for energy policy information in India and identifies their limitations.

3.2. Evolution of Conversational Systems

Conversational systems, commonly referred to as chatbots or virtual assistants, have been in use for several decades. Early conversational systems were based on simple rule-based mechanisms. These systems responded to user inputs using predefined patterns and scripted replies. While they demonstrated the possibility of human-computer interaction through language, they were limited in scope and unable to handle complex or unexpected queries. As computing power and data availability increased, conversational systems began incorporating machine learning techniques. These systems could recognise user intent and extract key information from queries, allowing for more flexible interactions. However, responses were still largely template-driven and required extensive manual configuration. In recent years, advances in artificial intelligence have significantly improved conversational systems. Modern systems can understand context, generate coherent responses, and adapt to different types of questions. This evolution has expanded the application of conversational systems beyond customer service to areas such as education, healthcare, and information services.

3.3. Artificial Intelligence for Information Access

Artificial intelligence has become an important tool for managing and accessing large volumes of information. Traditional information retrieval methods rely on keyword-based search, which requires users to know what terms to search for and how information is organised. AI-based systems reduce this burden by allowing users to interact using natural language. Research has shown that AI-powered question-answering systems can improve information accessibility by summarising content, answering direct questions, and presenting information in simplified forms. These systems are particularly useful in domains where information is complex, highly structured, or frequently updated.

In the context of public policy, AI can help translate technical documents into more understandable explanations. This capability is especially valuable for citizens and students who may not have expertise in policy analysis. By reducing complexity, AI systems can support greater public engagement and awareness.

3.4. Conversational AI in Governance and Public Policy

The application of conversational AI in governance is an emerging area of research and practice. Governments around the world have experimented with chatbots to provide information about public services, welfare schemes, and administrative procedures. These systems aim to improve service delivery, reduce administrative workload, and enhance citizen satisfaction. Studies suggest that conversational systems can be effective at answering frequently asked questions about government programs. They also help standardise responses and reduce misinformation. However, many existing government chatbots are limited to predefined question sets and cannot handle open-ended or analytical queries. In policy-related domains, conversational AI faces additional challenges. Policies are often complex, interconnected, and subject to frequent revisions. An effective policy-focused conversational system must adapt to these changes and provide context-aware responses. This requirement highlights the need for systems that can access updated information rather than relying solely on static knowledge.

3.5. Information Retrieval Approaches for Dynamic Domains

Information retrieval systems can broadly be categorised into static and dynamic approaches. Static approaches rely on stored documents or databases that are indexed for search. While these systems can be efficient, they require regular updates to remain accurate. In rapidly changing domains such as energy policy, maintaining an up-to-date database can be resource-intensive. Dynamic information retrieval approaches, on the other hand, fetch information in real time from external sources. This method ensures that users receive the most recent data available. However, it also introduces challenges related to response time, source reliability, and content consistency. Research indicates that combining conversational AI with real-time access to information can significantly improve the relevance of responses in dynamic domains. Such systems are better suited for policy environments where new announcements, amendments, and data releases occur frequently.

3.6. Existing Platforms for Energy Policy Information in India

India’s energy policy information is primarily disseminated through official government portals, regulatory authority websites, and published reports. Ministries such as the Ministry of Power and the Ministry of New and Renewable Energy regularly release policy documents, press releases, and statistical updates. In addition to government sources, research organisations and think tanks publish analytical reports and policy briefs. These documents provide valuable insights but are often written for specialised audiences. Media outlets also play a role in reporting policy developments, although coverage may vary in depth and accuracy. Despite the availability of these sources, there is no unified platform that allows users to interactively explore energy policy information. Users must manually navigate multiple websites and synthesise information from different formats. This fragmentation reduces efficiency and increases the risk of misunderstanding or outdated interpretation.

3.7. Limitations of Existing Solutions

The literature highlights several limitations in current approaches to energy policy information access:

- Government portals prioritise documentation over usability
- Policy documents are lengthy and complex to interpret ● Updates are scattered across multiple announcements
- Existing AI tools lack a domain-specific focus on Indian energy policies
- Most systems do not support conversational exploration of policy topics

These limitations suggest a clear need for a system that combines conversational interaction with reliable, up-to-date information access.

3.8. Research Gap and Need for the Present Study

While conversational AI has been successfully applied in several domains, its use for Indian energy policy information remains limited. Existing tools either lack specialisation or fail to provide real-time updates. The literature does not identify any widely used system that allows users to ask natural language questions specifically about Indian energy policies and receive current, synthesised responses. This project addresses this gap by developing a conversational system focused exclusively on Indian energy policy. By integrating conversational AI with real-time information retrieval, the system aims to overcome the limitations identified in existing solutions.

3.9. Relevance of Literature to Research on Energy Chatbot

The reviewed literature provides a strong foundation for the design choices made in this project. It supports the use of conversational AI for improving information accessibility, highlights the importance of real-time data in dynamic policy domains, and emphasises the need for user-centred design. The present research of this policy brief builds upon these insights by implementing a practical system that applies established concepts to a real-world problem. It contributes to existing work by demonstrating how conversational AI can be effectively adapted for public policy information dissemination in the Indian energy sector.

4. Methodology

4.1. Approach

The chatbot follows a practical, application-oriented approach. The focus is on designing and building a working system that addresses a real-world problem rather than developing new theoretical models.

4.2 Development Process

The system was developed in stages. Initial efforts focused on defining the scope and understanding user needs. This was followed by designing the chatbot logic, building the web interface, and testing the system with sample queries.

4.2. Information Sources

The chatbot retrieves information from official government portals, trusted research institutions, and reputable news organisations. These sources are selected to ensure accuracy and credibility. 4.4 Evaluation Criteria The system is evaluated based on:

- Clarity of responses
- Relevance to user queries
- Timeliness of information
- Ease of use
- Overall user satisfaction

5. Scenario Design

5.1. General Design

The system consists of a web interface where users can type questions and receive responses. Behind the interface, an AI component processes the query and determines whether additional information needs to be retrieved from online sources.

5.2. User Interface

The interface is designed to be intuitive and straightforward. Users interact with the system through a chat window similar to typical messaging applications. This design reduces the learning curve and makes the system accessible to a wide audience.

5.3. Information Flow

When a user submits a query, the system analyses the question, retrieves relevant information if needed, and generates a response. The final answer is presented in a clear and readable format.

6. Implementation Overview

6.1. Backend Logic

The backend manages user queries, processes responses, and retrieves information from external sources when required. It ensures that the system responds only to energy-related questions.

6.2. Frontend Functionality

The frontend displays the conversation and handles user input. It also provides visual feedback when the system is processing a query.

6.3. Data Handling

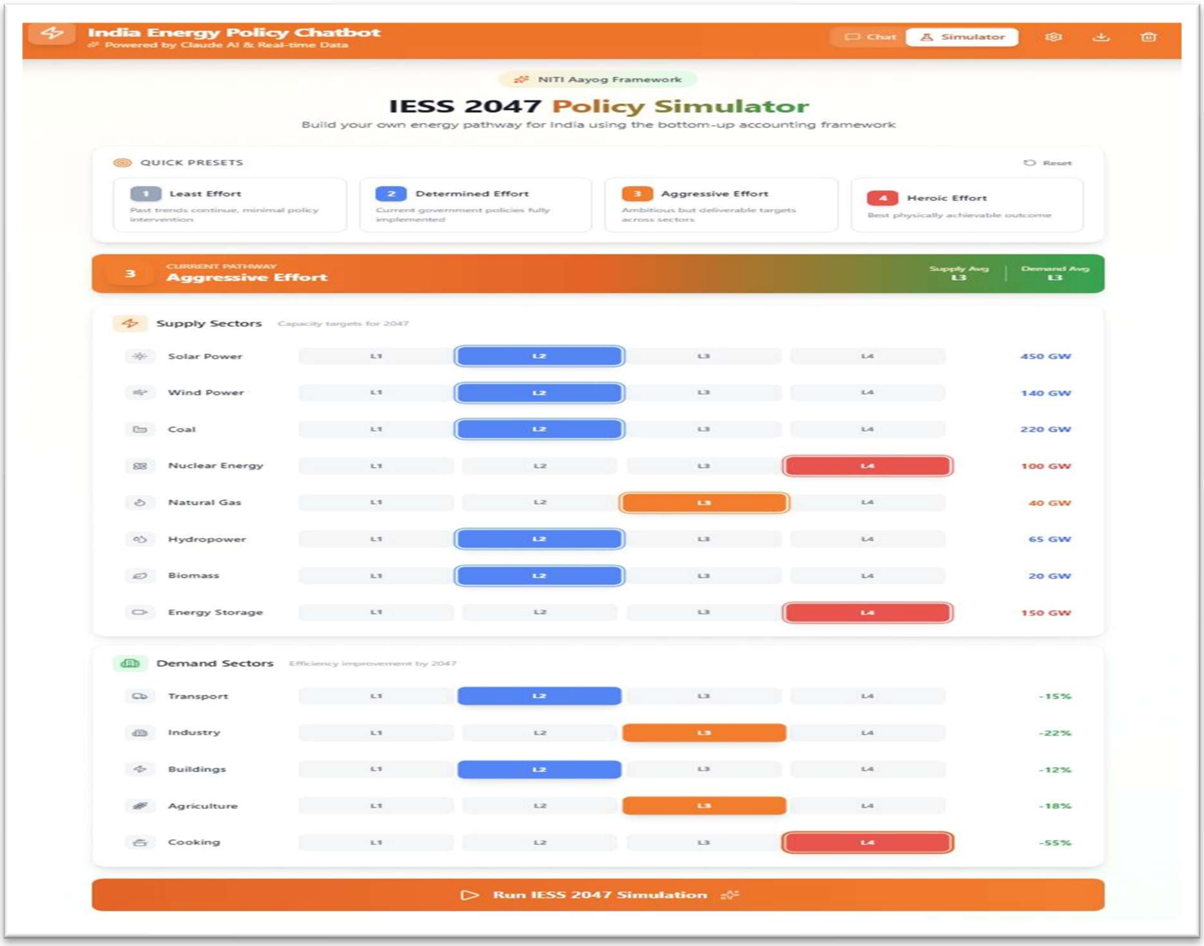
The system does not store personal user data. Each query is processed independently, which helps maintain privacy and simplicity.

7. Testing and Validation

The system was tested using a variety of questions related to Indian energy policies. These included factual, explanatory, and comparison-based queries. The responses were checked for clarity, relevance, and accuracy. User feedback was also considered to assess usability and satisfaction.

8. Results and Discussion

The chatbot was able to provide clear and relevant answers to most energy-related questions. Users reported that the system reduced the time required to find information and helped them understand complex policies more easily. However, the system depends on the availability and structure of online sources. Changes in website design can affect information retrieval. Additionally, the system currently supports only English-language interaction. A glimpse of the chatbot is given below –



IESS 2047 Policy Simulator

Build your own energy pathway for India using the bottom-up accounting framework

1 Least Effort – Past trends continue, minimal policy intervention

2 Determined Effort – Current government policies fully implemented

3 Aggressive Effort – Ambitious but deliverable targets across sectors

4 Heroic Effort – Best physically achievable outcome

CURRENT PATHWAY: 3 Aggressive Effort

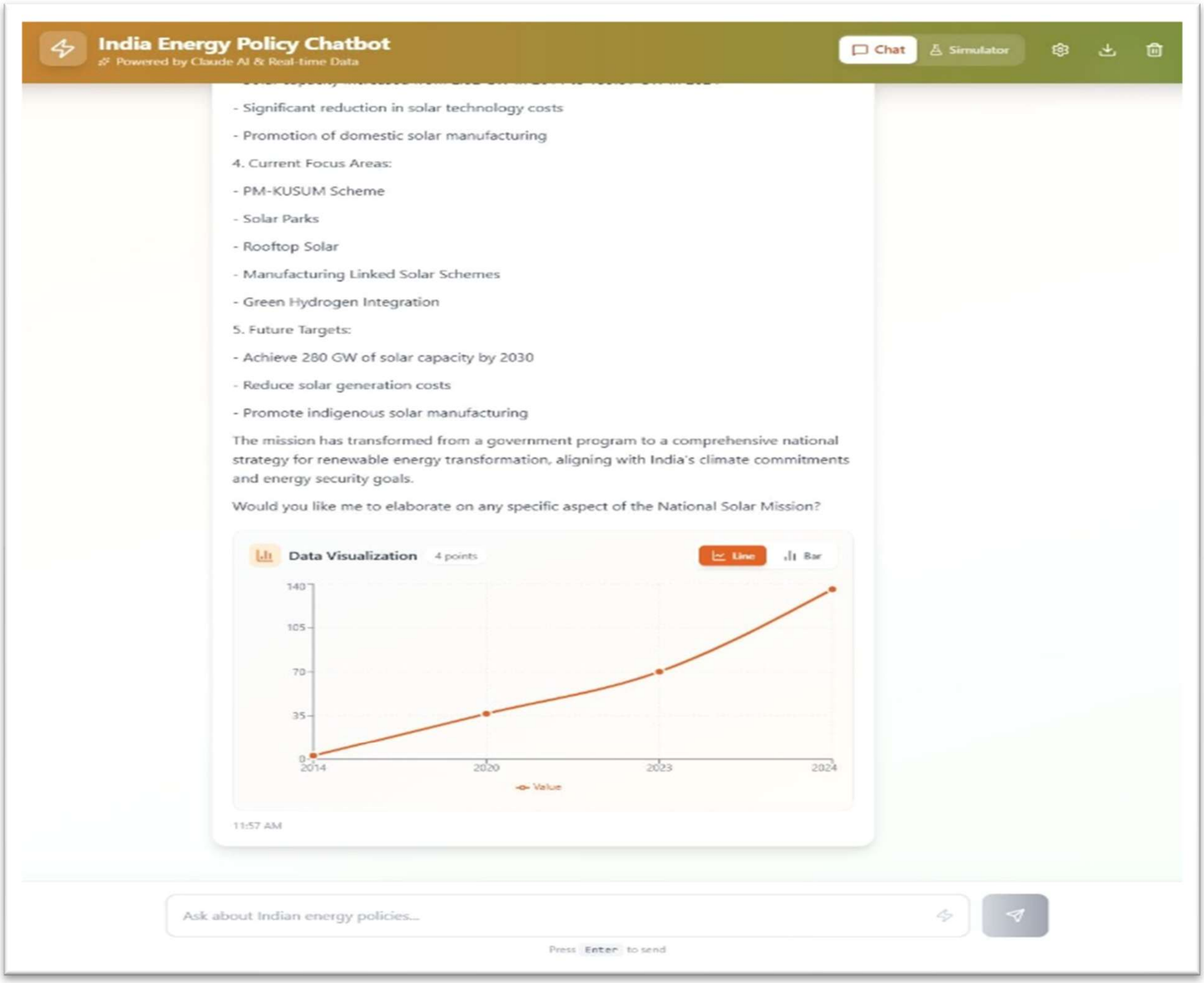
Supply Avg: L3 | Demand Avg: L3

Supply Sectors – Capacity targets for 2047

Sector	Level	Target
Solar Power	L2	450 GW
Wind Power	L2	140 GW
Coal	L2	220 GW
Nuclear Energy	L4	100 GW
Natural Gas	L3	40 GW
Hydropower	L2	65 GW
Biomass	L2	20 GW
Energy Storage	L4	150 GW

Demand Sectors – Efficiency improvement by 2047

Sector	Level	Improvement
Transport	L2	-15%
Industry	L3	-22%
Buildings	L2	-12%
Agriculture	L3	-18%
Cooking	L4	-55%



- Significant reduction in solar technology costs
- Promotion of domestic solar manufacturing

4. Current Focus Areas:

- PM-KUSUM Scheme
- Solar Parks
- Rooftop Solar
- Manufacturing Linked Solar Schemes
- Green Hydrogen Integration

5. Future Targets:

- Achieve 280 GW of solar capacity by 2030
- Reduce solar generation costs
- Promote indigenous solar manufacturing

The mission has transformed from a government program to a comprehensive national strategy for renewable energy transformation, aligning with India's climate commitments and energy security goals.

Would you like me to elaborate on any specific aspect of the National Solar Mission?

11:57 AM

9. Deployment

The application is deployed as a web-based system accessible through a standard browser. It uses cloud-based services to ensure availability and scalability while keeping costs low.

10. Conclusion and Future Scope

10.1. Conclusion

This policy brief demonstrates that conversational AI can play a valuable role in improving access to public policy information. By focusing on Indian energy policies, the chatbot provides a practical tool for students, researchers, and citizens.

The system shows that even with moderate technical complexity, AI-powered applications can deliver meaningful social impact.

10.2. Future Enhancements

Possible future improvements include:

- Support for regional languages
- Better handling of long policy documents
- Improved response speed
- Mobile-friendly interface
- Integration with official government data services

11. Some of The Data Sources for the Chatbot Development

- Ministry of Power, Government of India
- Ministry of New and Renewable Energy
- Central Electricity Authority
- NITI Aayog
- International Energy Agency
- React Documentation
- Express.js Documentation
- Open Data Source Models like Rumi, OSeMOSYS

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