Forecasting Energy Supply-Demand Dynamics in the Transport Sector and Its Linkage with Projected GDP Trends

B.Tech. project report submitted in partial fulfillment of the requirements for the award of Bachelor of Technology in Energy Engineering

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Under the Guidance of

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NEW DELHI – 110016

November 2025

Undertaking by the Student

I hereby declare that the work presented here in the report/thesis has been carried out by me towards the partial fulfilment of the requirement for the award of Bachelor of Technology in Energy Engineering at the Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The content of this report, in full or in parts, have not been submitted to any other institute or university for the award of any degree.

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CERTIFICATE BY THE SUPERVISOR(S)

This is to certify that the report/thesis entitled, "Title of project" being submitted by **Preksha Mishra (Entry No. 2022ES11849)** to the Department of Energy Science and Engineering, Indian Institute of Technology Delhi for partial fulfilment of the requirement for the award of degree of Bachelor of Technology in Energy Engineering. This study was carried out by him/her under my guidance and supervision.

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Date:

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1 Abstract

This project analyzes historical energy consumption in the **transport sector** across multiple fuels—petroleum products, compressed natural gas (CNG), ethanol, electricity, and emerging fuels. Historical data show that **petroleum has dominated** the sector, contributing over **90%** of total energy demand in 2023–24, with **road transport** alone accounting for nearly **81%**. While petroleum use continues to grow, trends indicate an approaching **saturation** in fossil fuel demand, opening space for alternative fuels. Although CNG, ethanol, and electricity currently represent relatively small shares of transport energy, they demonstrate **high growth momentum** driven by national policy targets and rapid technology adoption.

To understand potential future pathways, this study develops **long-term scenario projections** for three system-level cases—**Conservative Growth**, **Business-as-Usual (BAU)**, and **Accelerated Transition**. Using a **hybrid modelling framework** combining historical analysis, policy-driven targets, non-linear adoption curves, and a **displacement-based residual model** for oil and CNG, the scenarios provide a realistic and internally consistent assessment of India's transport energy trajectories. The results indicate that by 2050, alternative fuels could achieve a **substantially larger share** of transport energy, while total CO2 emissions diverge significantly across pathways due to differing rates of electrification and oil substitution. These findings offer important insights for **policy**, **infrastructure planning**, and India's long-term **energy security and decarbonisation objectives**.

2 Introduction

The **transport sector** is a critical component of India's economy. In 2023–24, it consumed over **5,790 PJ** of energy and emitted around **1,100 MtCO$_2$**, dominated by petroleum-based fuels. **Road transport accounts for nearly 85% of total energy consumption** [2].

India's transport energy landscape is undergoing rapid structural change, driven by increasing motorization, urbanization, and major policy initiatives, including renewable energy expansion, electric mobility, and biofuel blending mandates. Petroleum products have **historically dominated** the sector, but their growth trajectory is expected to **saturate** due to limited reserves, decarbonization pressures, and the emergence of technological alternatives in line with **Hubbert peak theory**.

Understanding **historical trends** and projecting **future energy demand** is essential for supporting long-term policy and infrastructure planning. This study employs a **hybrid modelling methodology** to analyze transport energy demand and develop three future scenarios—**Conservative Growth**, **Business-as-Usual (BAU)**, and **Accelerated Transition**. Through comparative scenario analysis across multiple fuel categories, this work highlights the **changing composition of transport energy** and its implications for India's **energy security**, **infrastructure investment**, and **net-zero transition**.

3 Literature Survey

Global research on transport energy transitions highlights the need for rapid decarbonization. The **IEA India Energy Outlook (2021)** [**?**] emphasizes that India will remain a **major driver of global oil demand**. BP Energy Outlook (2023) [13] and IRENA's World Energy Transitions Outlook (2022) [14] provide transition trajectories, though India-specific treatment is typically aggregated.

Nationally, **policy and planning institutions** provide detailed insights. The **NITI Aayog India Energy Security Scenarios (IESS) 2047+** [15] models multiple technology pathways for transport decarbonization, supported by projections from **MoPNG** and **TERI** [17] covering biofuels, CNG, and electric mobility. Government targets such as **20% ethanol blending (E20) by 2025–26** and **30% EV penetration by 2030** [16, 18] further motivate fuel substitution.

Fuel-specific research has focused on biofuel blending policies, lifecycle GHG benefits, and economic assessments of CNG and EV deployment. However, **hydrogen and methanol remain in pilot or experimental phases**. Existing literature often treats fuels independently, without explicitly modelling cross-fuel displacement or integrated emissions outcomes.

4 Research Gaps

From this review, several gaps are evident:

- **Limited integrated scenario-based modelling:** Most studies examine either a single fuel or an individual sub-sector; very few assess **system-wide** transport energy trajectories across multiple fuels within a consistent framework.

- **Insufficient modelling of cross-fuel interactions:** Existing forecasts largely neglect **displacement effects**, where increased electrification or ethanol blending directly reduces oil and CNG demand, risking overestimation of total energy use.

- **Limited long-term emissions quantification:** Few studies translate projected energy demand into **system-level CO_2 outcomes** aligned with national climate goals or carbon budget frameworks.

- **Inadequate assessment of supply-side feasibility:** Many studies assume supply capacity will match projected demand without analysis of domestic production constraints, energy imports, or renewable grid capability.

- **Data and temporal challenges:** Policy datasets emphasize dominant fuels and underrepresent emerging ones. The **COVID-19 anomaly period** is rarely accounted for, despite its distortion of growth trends.

5 Problem Definition

India's transport sector is a **major driver of energy demand and carbon emissions**, contributing nearly **13% of national final energy consumption** and around **12% of total CO_2 emissions** [15]. With national objectives to install **500 GW of non-fossil capacity by 2030**, reduce **cumulative emissions by one billion tonnes**, and achieve **Net Zero by 2070**, understanding the trajectory of transport energy demand is essential for planning.

Achieving these goals requires an integrated analysis that considers **interactions between fuels**, **future demand growth**, and the implications for **energy security**, **infrastructure**, and **policy**. This project therefore develops **scenario-based projections—Conservative Growth**, **Business-as-Usual**, and **Accelerated Transition**—that quantify energy demand, fuel contributions, and system-level emissions to evaluate credible transition pathways.

6 Objectives

1. **Historical benchmark analysis:** Analyze historical energy consumption, establish baseline trends, and derive the relationship between GDP growth and transport energy demand.

2. **Develop a robust multi-scenario model:** Construct long-term demand projections using a hybrid framework integrating policy targets, historical behaviour, and non-linear models

capturing saturation and technological adoption patterns.

3. **Projection formulation:** Develop granular projection equations for transport final energy demand and quantify energy intensity and efficiency trends, including a displacement-based residual model to capture cross-fuel substitution.

4. **Supply-side insight generation:** Evaluate feasibility considerations for each scenario, including domestic production and import dependencies to support policy and investment planning.

5. **Emissions quantification:** Translate projected energy use into sector-wide CO_2 emissions to assess alignment with national climate objectives.

7 Methodology

The methodology in this study aims to project transport energy demand across multiple fuels using a **hybrid forecasting framework**. This approach integrates **policy-driven targets, historical trend analysis, non-linear adoption modelling, and a displacement-based residual forecasting model** to generate realistic long-term projections. The model is organized by fuel type to capture mode- and technology-specific dynamics while enabling aggregation at the national transport system level. The same framework is subsequently extended to develop three system-wide scenarios—**Conservative Growth**, **Business-as-Usual (BAU)**, and **Accelerated Transition**—implemented through a smooth scaling approach between 2024–2050.

This hybrid approach was chosen to leverage the strengths of multiple forecasting techniques and mitigate their individual limitations. It enables the use of policy-aligned, target-based modelling for emerging sectors such as electric vehicles (EVs) and ethanol, where historical data are limited and growth is driven by mandates. For mature fuels like oil and CNG, where historical trajectories are long and stable but now subject to substitution effects, a **residual displacement model** is employed such that the projected growth of alternative fuels directly reduces demand for petroleum-based fuels instead of allowing independent growth. This ensures internally consistent projections and captures interactions across fuel categories.

To quantify historical growth, the CAGR for each fuel and sector is calculated as:

$$\text{CAGR} = \left(\frac{E_{\text{final}}}{E_{\text{initial}}}\right)^{\frac{1}{n}} - 1$$

where E_{initial} and E_{final} denote the consumption in the first and last years of the dataset, and n is the number of years between them. Future energy demand is then projected according to:

$$E_t = E_{\text{base}} \times (1 + \text{CAGR})^{(t - t_{\text{base}})}$$

To ensure robustness and prevent distortions caused by the COVID-19 anomaly, historical data from 2020–22 were excluded from CAGR estimation. However, several fuels still exhibit a visible rebound dip during this period in raw historical traces.

CSV files containing historical and projected values for each fuel are provided in the Appendix. As per the conventions of international bodies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC), Net Calorific Values (NCVs) are used to standardize all energy calculations. NCV values used in this study are shown in Table 1:

Table 1: Net Calorific Values of Different Fuels

Fuel type	Net Calorific Value (NCV) (MJ/kg)
High Speed Diesel	47.07
Light Diesel Oil	41.00
Motor Spirit (Petrol)	44.56
Furnace Oil	39.96
Liquefied Petroleum Gas	44.98
Aviation Turbine Fuel	40.13
CNG	44.50
Ethanol	27.14

7.1 GDP–Driven Transport Energy Demand Projection

Historic data collection was conducted as follows:

1. **Total GDP** in current USD was obtained from the World Bank global database [1].
2. Historical **final energy consumption by the transport sector** was sourced from the International Energy Agency (IEA) balances [3].

With both GDP and transport final energy demand available for the period **2002–2024**, the **Energy Intensity (EI)** of transport was computed directly as:

$$EI_t = \frac{ED_t}{GDP_t} \tag{1}$$

where EI_t is the transport energy intensity in year t (Mtoe per trillion USD), ED_t is historical transport energy demand (Mtoe), and GDP_t is total GDP (trillion USD).

A long–term trajectory for energy intensity was then derived by applying an exponential decay model. Since very early years exhibit high volatility, the EI trend was fitted only across the period **2009–2024**, yielding a smoother and statistically meaningful decline. The decay rate r was calculated as:

$$r = \left(\frac{EI_{2009}}{EI_{2024}}\right)^{\frac{1}{15}} - 1 \tag{2}$$

which produced a value of:

r = 0.01794 (**1.794% annual reduction in EI**)

The future projection of energy intensity therefore follows:

$$EI_t = \frac{EI_{2024}}{(1+r)^{(t-2024)}} \tag{3}$$

Using the derived EI decay, the **transport energy demand forecast** for 2025–2050 was obtained using the equation:

$$ED_t = GDP_t \times EI_t \tag{4}$$

where GDP_t is the externally projected GDP series and EI_t the computed intensity trend.

This formulation explicitly links macroeconomic expansion and sectoral energy demand while separating growth effects from efficiency improvements. Since efficiency has historically improved gradually, a constant proportional decay rate was employed rather than assuming disruptive step changes. The result is a trajectory where **GDP continues to grow strongly**, while

energy demand grows more slowly due to declining energy intensity, making decoupling visually and analytically clear.

The combined historical and projected curves for GDP and transport energy demand, and the projected energy intensity trend, are presented in Figures 1 and 2.

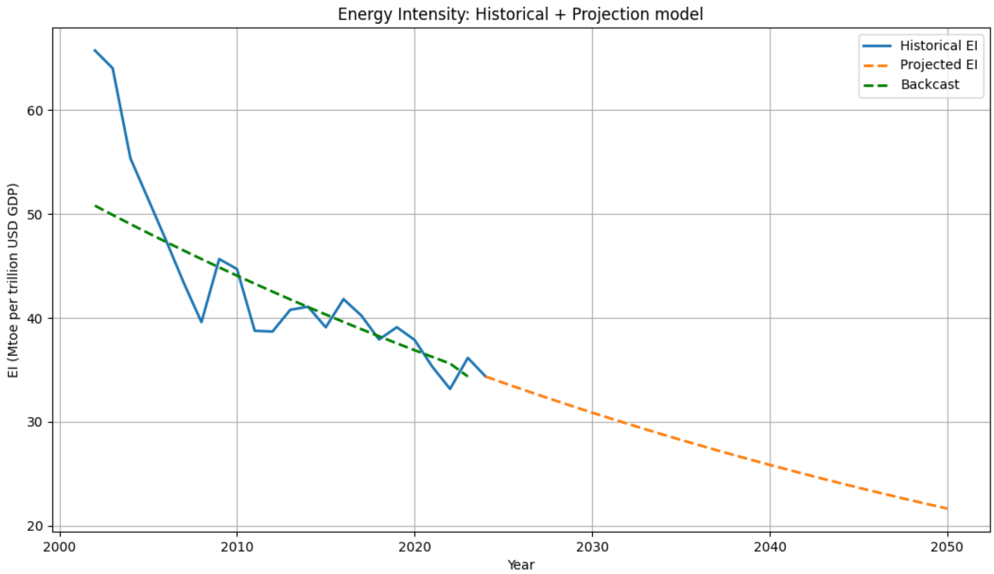


Figure 1: Historical and projected transport energy intensity (EI) in India till 2050

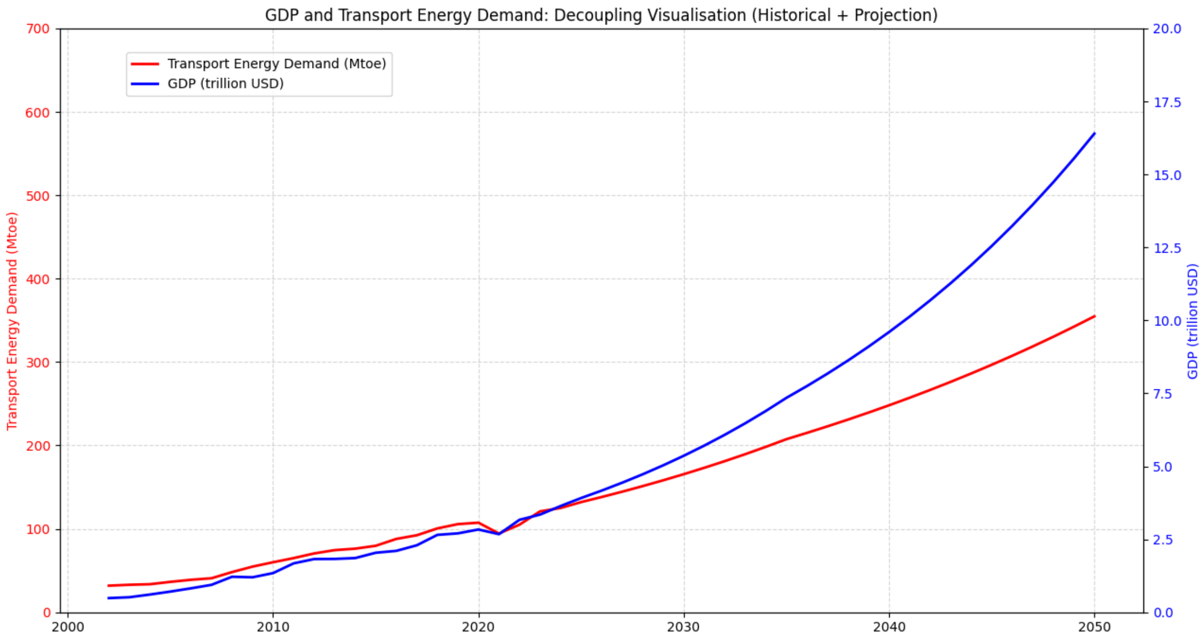


Figure 2: Historical and projected total GDP and transport energy demand (ED) for India till 2050

To contextualize the projected transport energy demand within India's broader energy transition, the **fuel-wise composition of total final energy consumption (TFEC)** was also evaluated.

The percentage shares for the years **2000**, **2010**, **2020**, and **2021** were sourced from the **IEA Balances database** [3]. Intermediate yearly values between these anchor points were obtained via **linear interpolation**, ensuring a smooth historical trend. For future years, the TFEC composition was aligned with long-term national decarbonization expectations. Specifically, the following sector-level fuel mix targets were assumed:

Energy Category	**2030 Share (%)**	**2047 Share (%)**
Coal	45	25
Oil + Gas	30	20
Traditional Biomass	3	3
Modern Renewables	13	43
Other	9	9

Table 2: Assumed Total Final Energy Mix Shares Used for Forward Projections.

For all intermediate years (between 2021–2030 and 2030–2047), the shares were **linearly interpolated**. This ensures a continuous and policy-consistent evolution of TFEC composition, reflecting a gradual decline in coal and traditional biomass alongside a **progressive rise in modern renewable energy penetration**. The resulting mix trajectories are shown in figure 3 and subsequently used to map **fuel-wise contributions** to total transport sector energy and emissions.

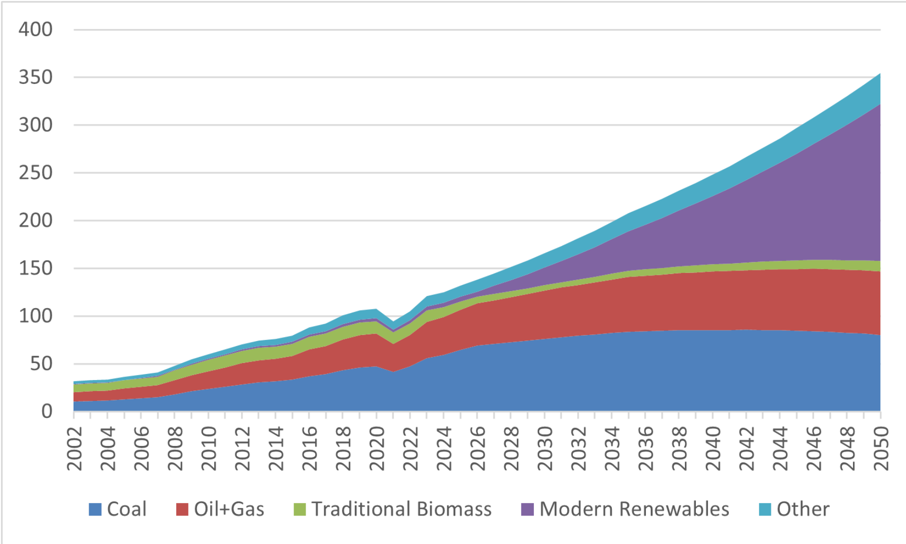


Figure 3: Total Final Energy Mix- Historical Data and Projection for India till 2050

7.2 Electric Vehicles (EVs)

7.2.1 Demand-side Estimation

Historical energy consumption data for the EV sector was sourced from the **Bureau of Energy Efficiency (BEE)** [5]. Since large-scale EV adoption in India has occurred primarily post **2022**, using raw historical values to compute a growth rate results in an unrealistically high **127%** CAGR. To avoid this distortion, a **target-based forecasting** methodology was adopted.

Historical data for total registered vehicles and registered EVs was obtained from the **NITI Aayog Energy Dashboard** [2]. National EV penetration goals for **2030**, as stated in government policy [6], include:

Vehicle Category	**Target EV Penetration by 2030**
Two- and Three-Wheelers	80%
Commercial Cars	70%
Private Cars	30%
Buses	40%

Table 3: Government EV Penetration Targets for 2030 [6].

These penetration levels were applied to the projected vehicle population in 2030 to derive a more realistic EV fleet estimate. The resulting CAGR for EV energy demand was calculated to be **59.99%**, which was used for projections up to **2045**. Beyond this point, the EV market is assumed to approach saturation, and an **S-curve adoption model** was fitted such that EVs constitute **60%** of the national fleet by **2050**. The equation obtained for the logistic curve is as follows, where t is the distance from base year 2023:

$$E(t) = \frac{17147.8074}{1+\exp(-0.4734(t-20.6910))} \tag{5}$$

7.2.2 Supply-Side Estimation

To determine the electricity **supply** allocated to EVs, the historical ratio of EV electricity demand to total national electricity demand was computed. The latest value of this ratio (corresponding to full scale deployment in 2024) will remain fixed on the demand and supply side due to the independence of transmission and distribution (T&D) losses with application. Total electricity **generation** was multiplied by this share to obtain the electricity **supplied to EVs**. Historic data for other electricity applications reveal fixed **Demand/Supply ratio**, indicating stable grid efficiency. Therefore, this ratio was held constant at the latest value for electricity consumption by EVs (equal to 0.889) for all projected years, thereby ensuring consistency in assumed T&D loss percentages across the timeframe of analysis. The demand and supply curves are shown in figure 4.

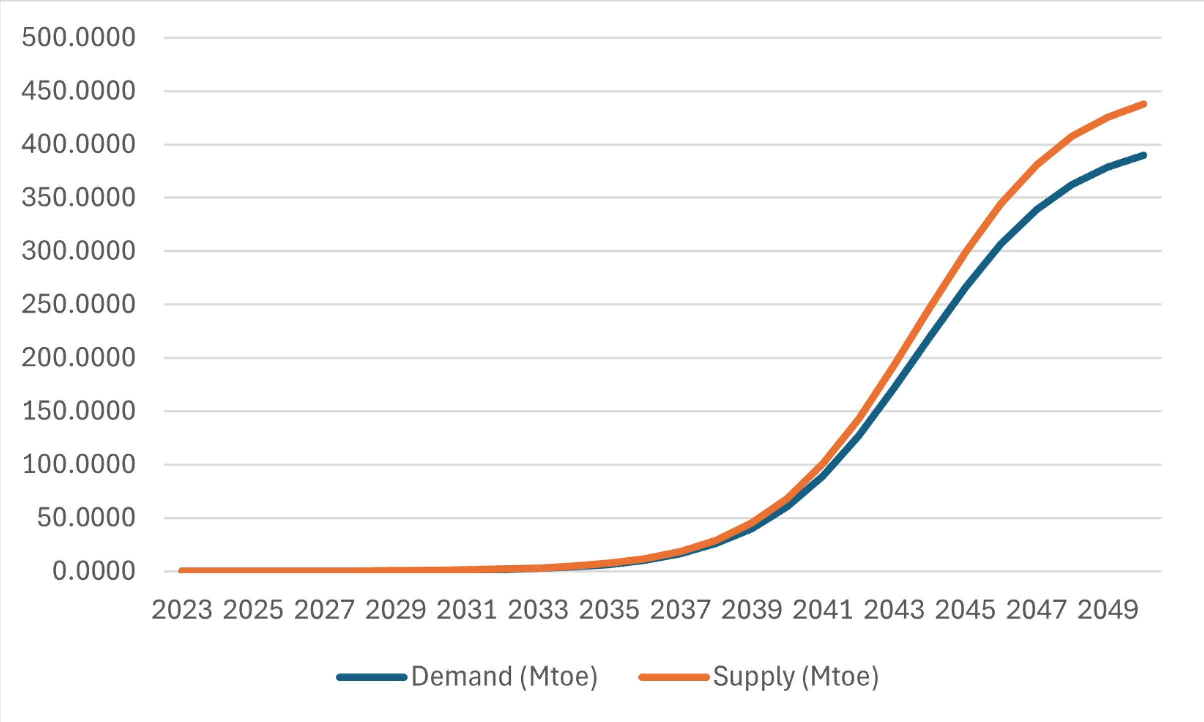


Figure 4: Projected Energy Demand and Supply from EVs in India till 2050

7.2.3 Fuel-Wise Attribution

To apportion the EV electricity supply across primary energy sources, the **national electricity generation mix** was used. The fractional shares of **coal**, **oil and gas**, **hydro**, **nuclear**, and **renewable energy (solar, wind, biomass, small hydro)** in total electricity generation were applied to the EV electricity supply to determine the contribution of each fuel to EV charging.

For future projections, the generation mix was aligned with government decarbonization pathways [7, 8, 9]. The assumed generation mix for the projection years is given below:

Energy Source	**2030 Share (%)**	**2047 Share (%)**
Coal	45	30
Oil + Gas	8	5
Hydro	8	10
Nuclear	4	5
Renewables (Solar, Wind, Biomass, Small Hydro)	35	50

Table 4: Projected Electricity Generation Mix for 2030 and 2047 Based on National Decarbonization Targets.

Applying these mixes to the projected EV electricity supply, with linear interpolation for intermediate years, allows for a **fuel-specific attribution of the EV sector's energy footprint** (shown in figure 5), which will be used subsequently in the **emissions assessment** and system-level scenario comparisons.

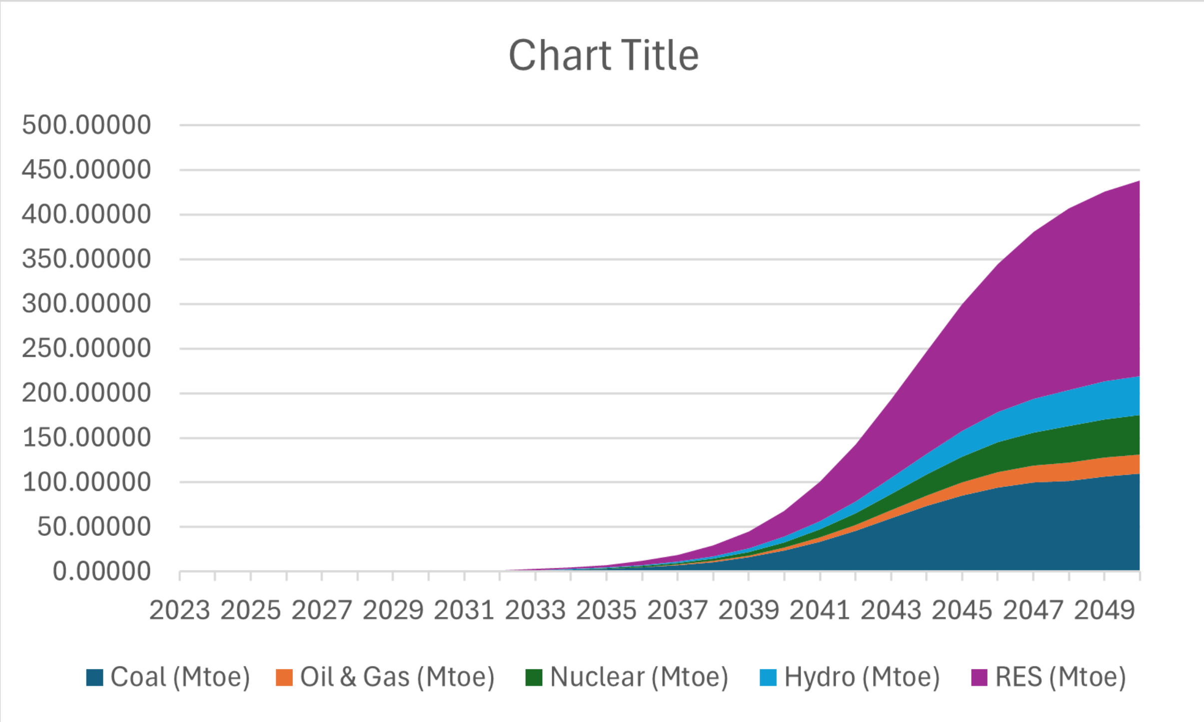


Figure 5: Projected Energy Mix for EV Electricity Supply in India till 2050

7.3 Railways Electrification

7.3.1 Demand Side Estimation

Energy consumption data for the railway sector from 2006 to 2024 were sourced from the **NITI Aayog Energy Dashboard**[2]. As of **2024**, Indian Railways has achieved **98%** electrification of the broad-gauge network, with a target of **100%** electrification by **2026**, as stated by the Ministry of Railways[10]. The energy consumption corresponding to complete electrification was estimated using a unitary scaling, and this value is assigned to all post-2026 years.

To forecast electricity demand for railway traction, multiple functional forms were fitted to the historical consumption data, as shown in figure 6.

Each model was evaluated using a **cross-validation adjusted R^2** metric to prevent overfitting and ensure robustness. The model that produced the highest CV-adjusted score of 0.9801 was the **Piecewise Linear + Logistic** hybrid. This form captures a linear increase till 2017, followed by a rapid growth then saturation captured by the logistic leg. The function is second degree smoothed at the break point for differentiability in the whole range. The equation of the curve is as follows:

$$
\begin{aligned}
E(t) = &\left(1 - \frac{1}{1+\exp(-1.2\,(t-7))}\right)(0.0626t + 0.9461) \\
&+ \frac{1}{1+\exp(-1.2\,(t-7))}\left(\frac{1.2300}{1+\exp(-1.4046\,(t-12.9542))} + 1.4380\right)
\end{aligned}
\tag{6}
$$

This model accurately reproduces the observed consumption rise through 2024 and the expected plateau after 2026.

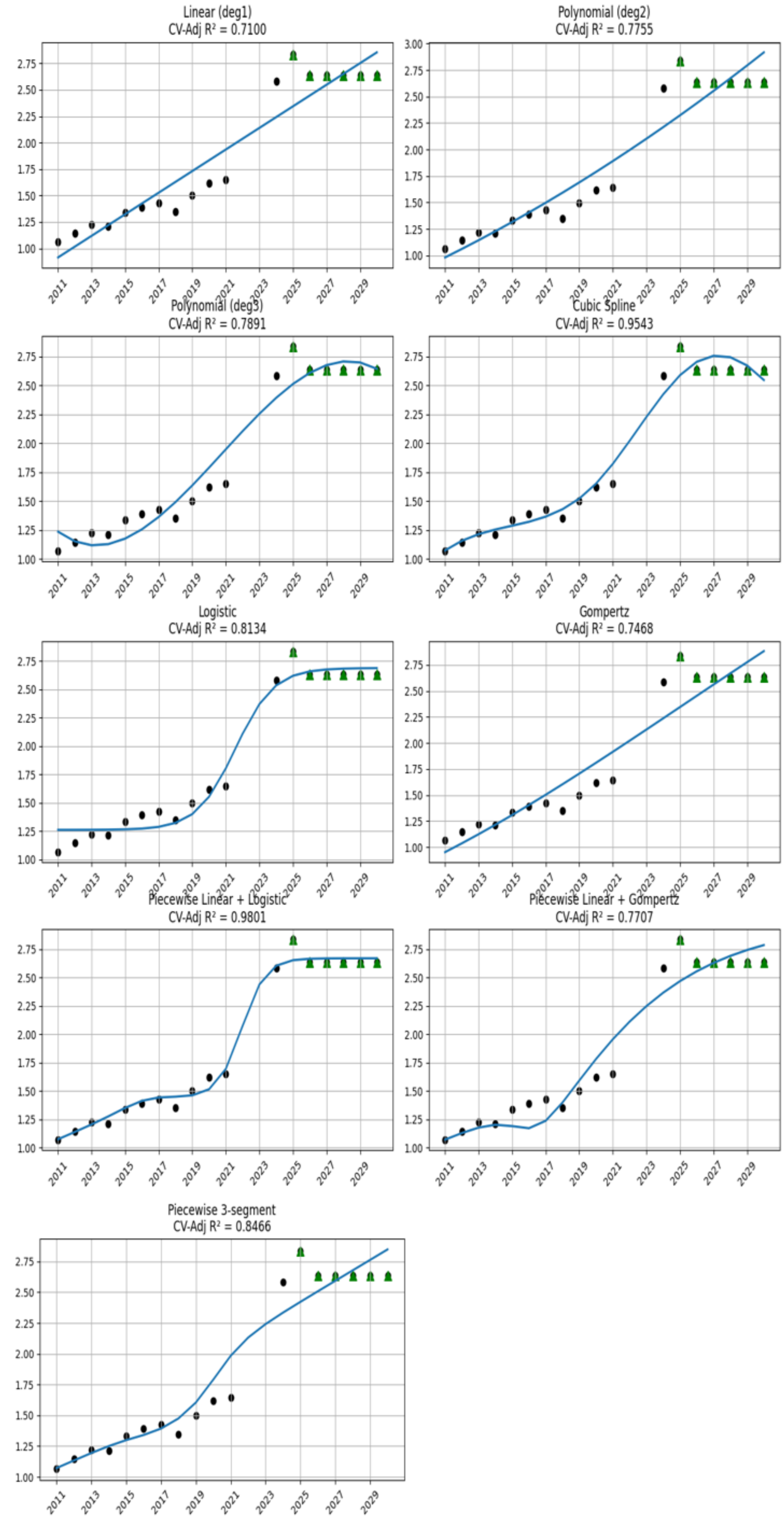


Figure 6: Curve Fitting for Electricity Consumption by India Railways till 2030

7.3.2 Supply-Side Estimation

The methodology for deriving the **electricity supply requirement** mirrors that used for the EV sector. Specifically:

1. The historical ratio of **electricity demand/supply** was computed to capture T&D losses.
2. This ratio was held constant for projection years, reflecting stable T&D loss fractions.
3. The projected railway electricity demand was thus scaled to obtain its **required supply**.

To determine the **fuel-wise contribution** to the electricity used in the railway sector, the same source attribution procedure applied in the EV analysis was adopted. The projected electricity generation mix follows the nationally aligned decarbonization pathway (Table 4), and the corresponding shares of coal, oil & gas, hydro, nuclear, and renewables were applied proportionally to the railway electricity supply.

The plots for the supply and demand for electricity by Indian railways is shown in figure 7.

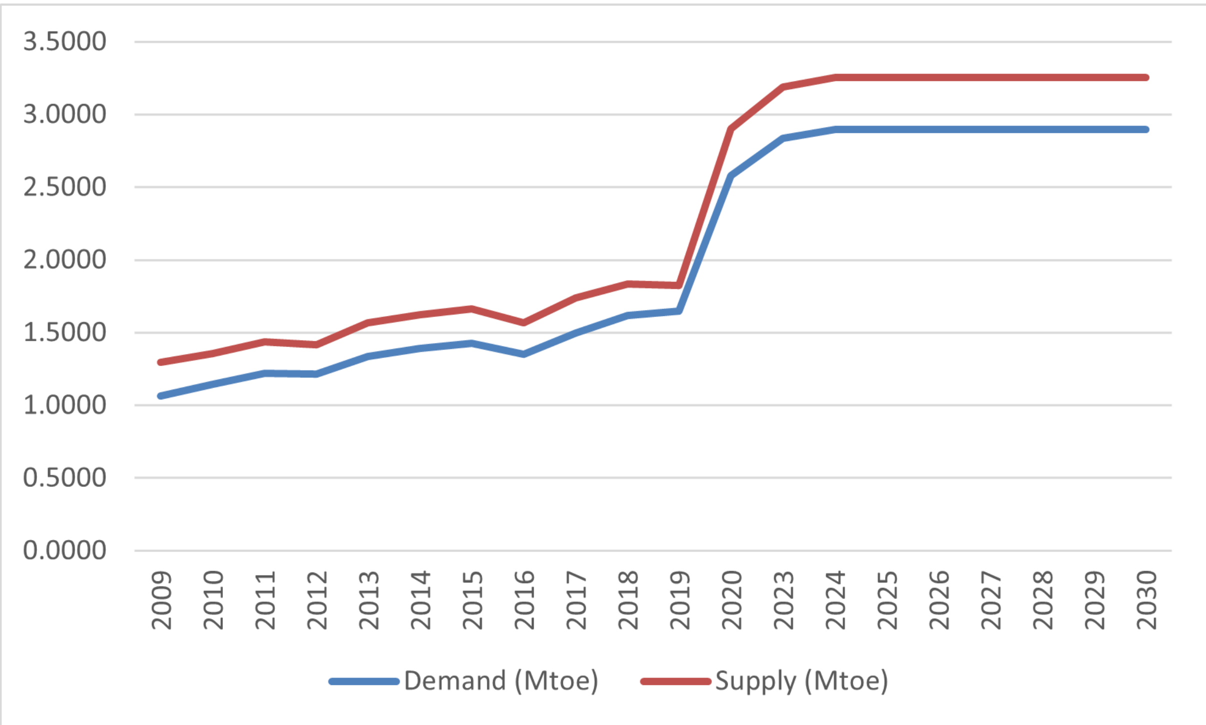


Figure 7: Projected Electricity Demand and Supply for Indian Railways till 2050

7.3.3 Fuel-Wise Attribution

To determine the contribution of **primary fuels** to railway electrification, the same **fuel attribution framework** adopted for the EV sector was applied.

1. The projected railway electricity supply is allocated across fuels using the national generation mix (Table 4).

2. Shares for intermediate years are linearly interpolated between 2030 and 2047.

3. This provides fuel-wise railway electricity consumption for subsequent emissions assessment.

This approach enables a **bottom-up allocation** of electricity-related emissions to the railway sector and allows direct comparison with the EV sector in later **cross-modal decarbonization analysis**.

The resulting plot for **fuel-wise attribution** is illustrated in Figure 8.

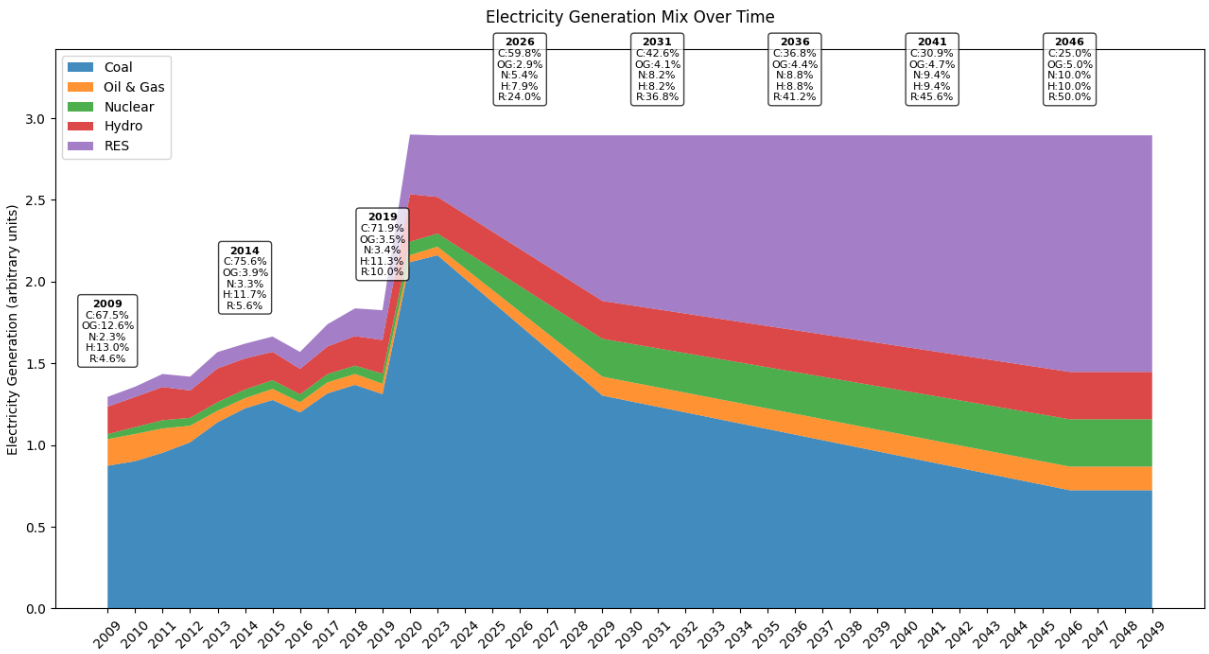


Figure 8: Projected Energy Mix for Railway Electricity in India till 2050

7.4 Ethanol Forecasting

Historic ethanol consumption data from **2015** onward was collected in litres from the **NITI Aayog Energy Dashboard**[2]. A direct calculation of the CAGR from this historical data yielded an unrealistically high **23.76%**. To establish a more representative and policy-aligned forecast, a **target-based approach** was adopted.

India has already achieved an **E20 blend in 2025** and aims to achieve **E25 by 2030**, as stated by the Ministry of Petroleum and Natural Gas (MoPNG) [16]. Projected petrol consumption volumes were used to determine the corresponding ethanol requirements for these blend levels. Using the **2025 and 2030 target points**, a revised CAGR of **13.2%** was computed, which was then applied to forecast ethanol consumption.

Since ethanol is a **liquid transport fuel** directly blended into petrol, its **demand equals supply under steady-state market conditions**. That is, the volume of ethanol consumed in transport directly corresponds to the volume that must be produced or imported, without additional transformation or conversion losses. Therefore, **the projected consumption also represents the projected supply requirement** for the sector, as shown in Figure 9. The equation obtained is as follows, where 2015 is taken as base year:

$$E(t) = 2.490451 \cdot (1 + 0.13199770)^t \tag{7}$$

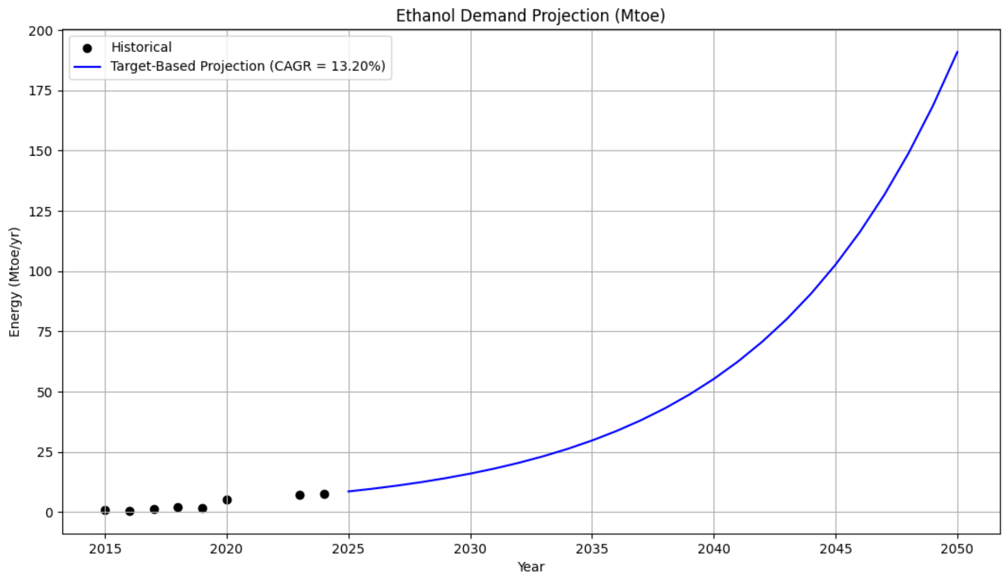


Figure 9: Projected Energy Demand and Supply from Ethanol in Blended Petrol in India till 2050

7.5 Oil and CNG

The projection for total final energy consumption by the transport sector was used as the basis for forecasting oil and CNG consumption. Once again, since both oil and gas are transport fuels, their supply is the same as their consumption. A rudimentary analysis for projecting hydrogen and methanol consumption indicated that their contribution to the total energy demand would be negligible, and thus, they were safely excluded from this analysis. The forecasting was achieved by subtracting the projected energy consumption values for EVs, electrified railways, and ethanol. This approach provides a combined projection for oil and CNG consumption that accounts for the transition to alternative fuels. As shown in Figure 10, this results in a noticeable dip in their combined energy consumption post-2040.

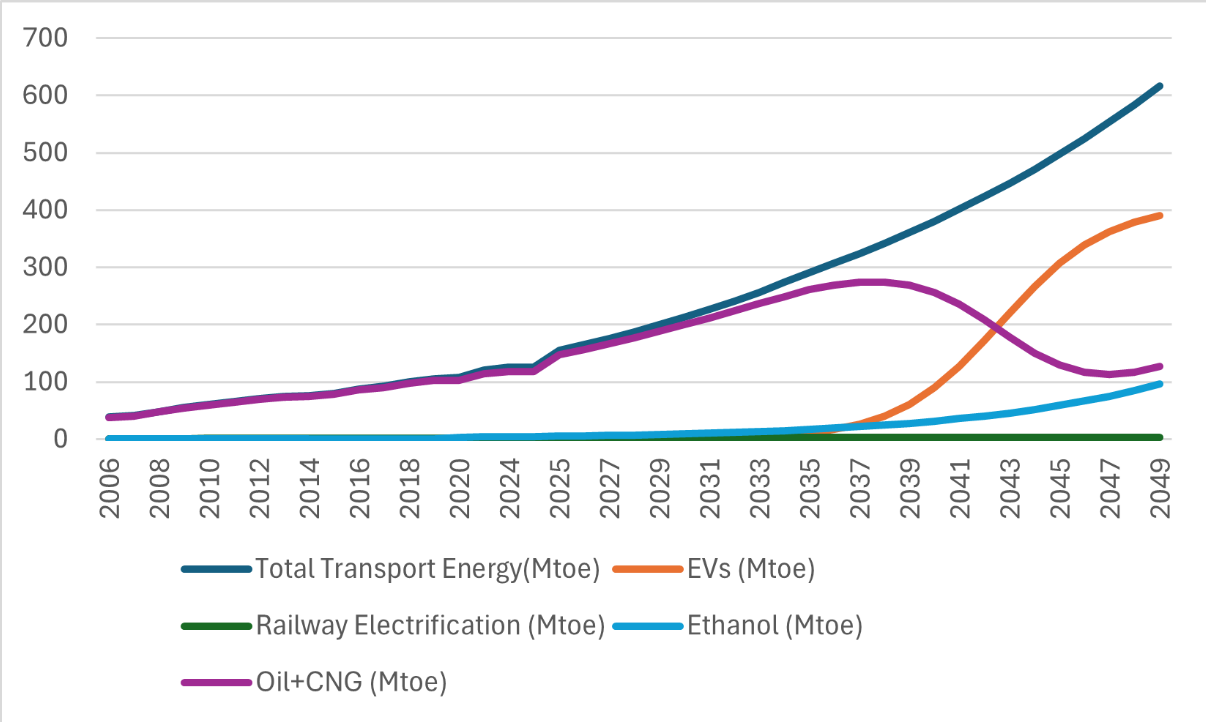


Figure 10: Projected Energy Demand all Major Fuels in India till 2050

Historical data for the sub-fuels of oil and CNG were collected from the **NITI Aayog Energy Dashboard**[2]. For oil, sub-fuel consumption in tonnes was multiplied by their respective Net Calorific Values (NCVs) and aggregated to obtain the total historical energy consumption for oil. For CNG, only the total natural gas (CNG + LNG) consumption data is available. A **2023** value of **5.4 MMT** was found to be consistent with the CNG consumption in road transport value given in a **CEEW** report [12], confirming that the total natural gas data could be used as a representative value for CNG in the road transport sector.

In **2024**, the energy consumption values for oil and CNG were calculated to be **125.786 PJ** and **6.006 PJ** respectively, establishing an approximate ratio of **20:1**. This ratio is assumed to remain constant until **2050**, allowing the combined oil and CNG projections to be split into individual forecasts. A comparison of this methodology's oil and CNG projections with those based on traditional CAGR are shown in Figure 11 and Figure 14, showing a significant discrepancy thus validating the more nuanced approach.

Oil Sector

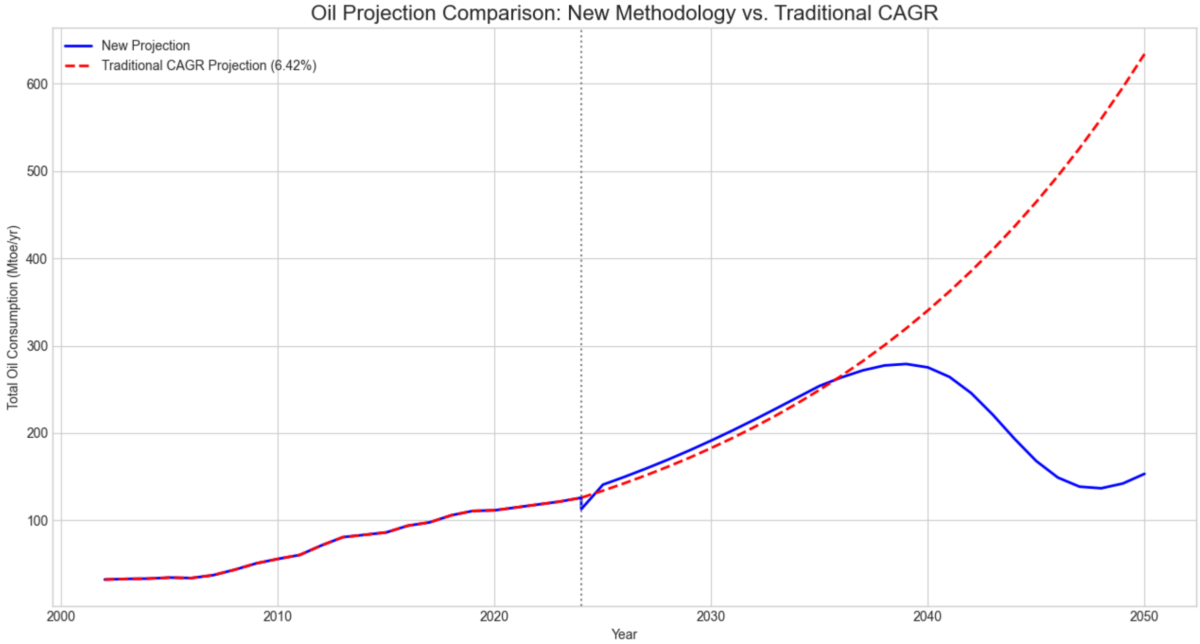


Figure 11: Projected Energy Demand from Oil in Road+Railway+Aviation+Shipping Sectors in India till 2050

Figure 12 shows the contribution of the four subsectors of transport in the energy demand met using oil in India. This is determined by observing a near constant contribution of 87% for road, 4% for railway, 6% for aviation, and 3% for shipping. These numbers are used to determine the individual splits for the projected years.

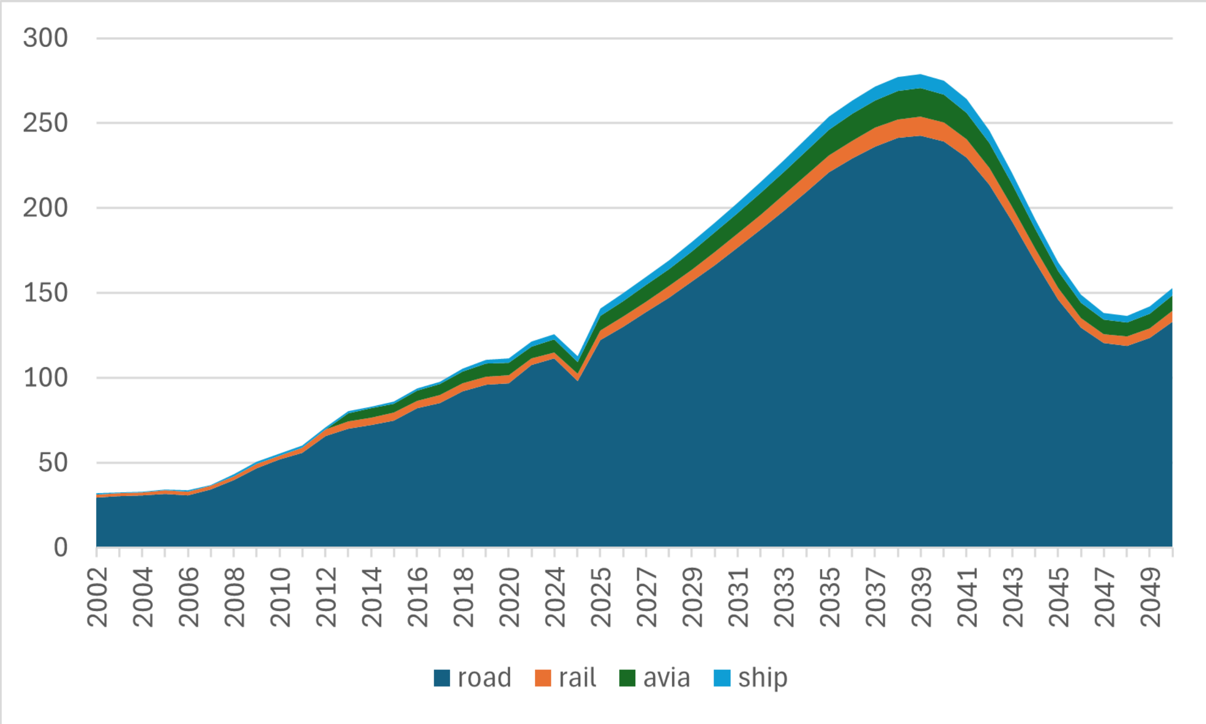
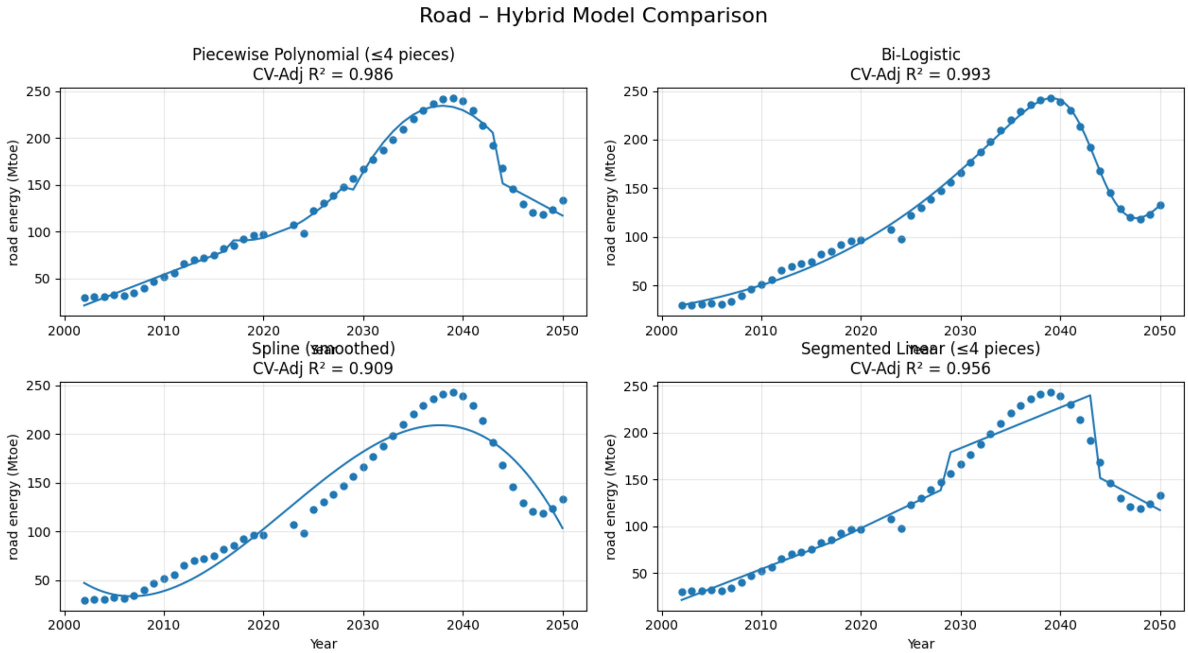
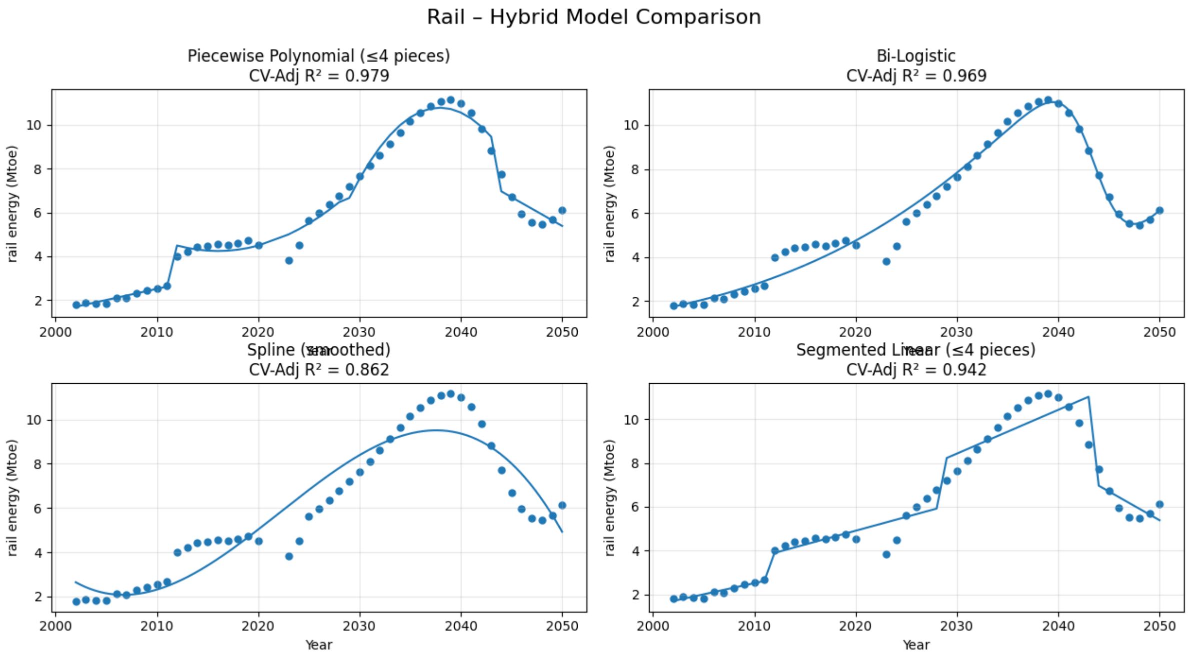


Figure 12: Subsector Contribution in Energy Demand from Oil in India till 2050

Historical and projected oil consumption for each transport subsector was independently fitted using four competing modelling approaches selected for their complementary structural characteristics: (i) **Piecewise Polynomial Regression** (up to four segments) to approximate non-linear behaviour with breakpoint-driven slope transitions, (ii) **Bi-Logistic growth–peak–decline** modelling, appropriate for technology diffusion and resource-transition trajectories exhibiting saturation effects, (iii) **Cubic Spline smoothing**, providing high shape flexibility using curvature-controlled knots, and (iv) **Segmented Linear Regression**, representing structural turning points in a parsimonious form. Model performance was evaluated using **Cross-Validated Adjusted R^2**.

As observed from the fitted curves in Figure 13, the Piecewise Polynomial model **overfits historical fluctuations**, resulting in unrealistic sharp curvature and oscillatory behaviour. The Cubic Spline and Segmented Linear models **struggle to capture the expected peak and post-transition decline**, leading to poor representation of behavioural dynamics beyond 2040. In contrast, the **Bi-Logistic model achieves the highest CV-Adjusted R^2 performance for all subsectors**, accurately reproducing both the historical growth trajectory and the anticipated decline driven by electrification, efficiency improvements, and alternative fuel adoption.


Road – Hybrid Model Comparison
Piecewise Polynomial (≤4 pieces)
CV-Adj R² = 0.986
Bi-Logistic
CV-Adj R² = 0.993
Spline (smoothed)
CV-Adj R² = 0.909
Segmented Linear (≤4 pieces)
CV-Adj R² = 0.956
road energy (Mtoe)
Year


Rail – Hybrid Model Comparison
Piecewise Polynomial (≤4 pieces)
CV-Adj R² = 0.979
Bi-Logistic
CV-Adj R² = 0.969
Spline (smoothed)
CV-Adj R² = 0.862
Segmented Linear (≤4 pieces)
CV-Adj R² = 0.942
rail energy (Mtoe)
Year

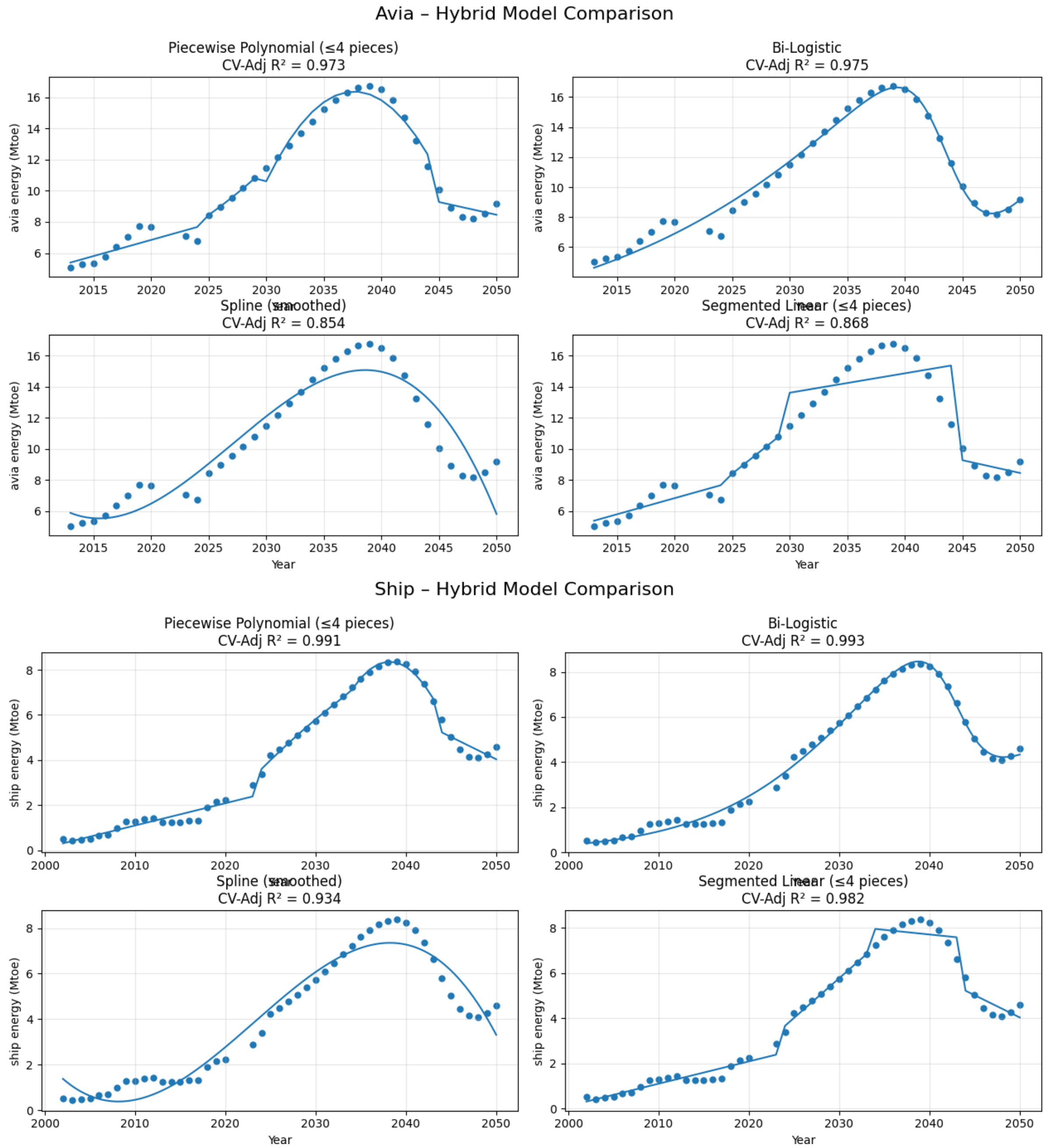


Figure 13: Hybrid Curve Fitting Results for Oil Subsectors (Road, Rail, Aviation, Shipping)

The general form of the Bi-Logistic model used for fitting is given by:

$$E(t) = \frac{A}{1+e^{-k_1(t-t_1)}} - \frac{B}{1+e^{-k_2(t-t_2)}},$$

and Table 5 presents the corresponding optimised parameter values $(A, k_1, t_1, B, k_2, t_2)$ obtained for each subsector based on historical data.

Table 5: Bi-Logistic Best-Fit Parameters for Oil Subsectors

Sector	A	k1	t1	B	k2	t2	CV-Adj R^2
road	473.0052	0.112586	2002	542.0241	0.062469	2039	0.8415
rail	24.1132	0.098586	2002	28.1285	0.059318	2039	0.7866
avia	27.1590	0.082282	2013	12.9908	0.744910	2039	0.9640
ship	12.1525	0.158682	2002	12.0716	0.068217	2039	0.8654

CNG Sector

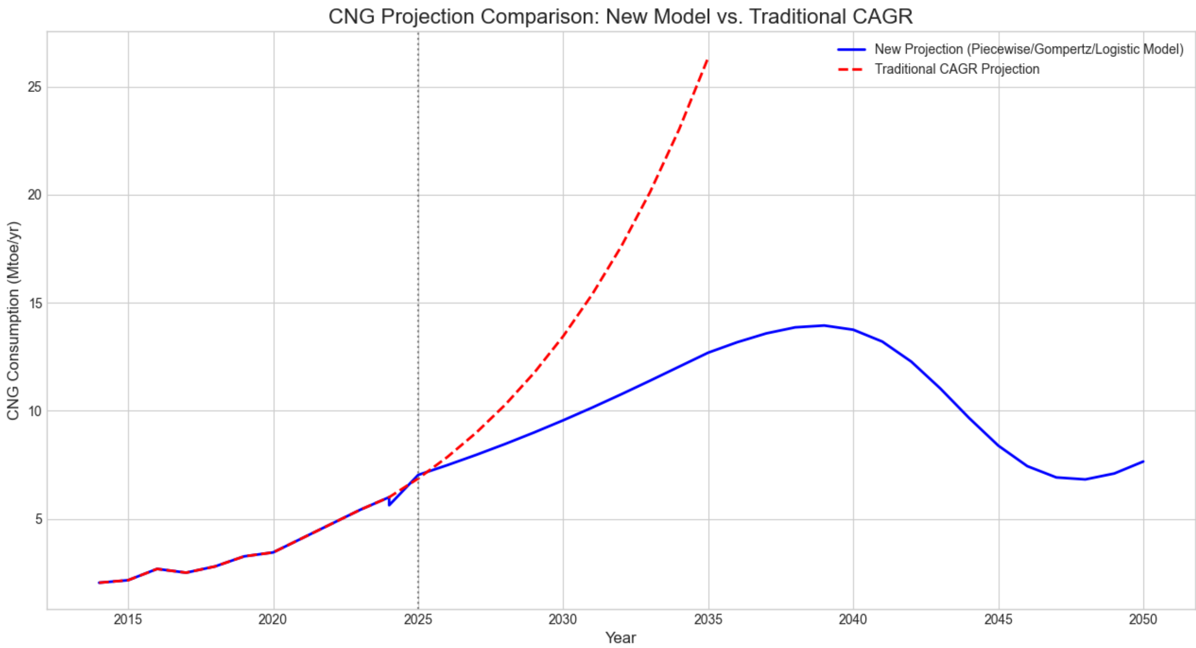


Figure 14: Projected Energy Demand from CNG in Road Transport in India till 2050

Similar to the methodology followed for oil, historical and projected CNG consumption was modelled using a comparative curve-fitting framework comprising four alternative regression families: (i) **Piecewise Polynomial Regression** with up to four segments governed by optimally detected breakpoints, (ii) **Bi-Logistic growth–peak–decline** structure capable of representing saturation and transition-driven decline, (iii) **Cubic Spline smoothing**, and (iv) **Segmented Linear Regression**. Model performance was assessed using **Cross-Validated Adjusted R^2** to ensure robust generalisation rather than local interpolation accuracy.

Figure 15 illustrates the relative performance of the four models. As in the case of oil subsectors, the **Piecewise Polynomial fit exhibits overfitting behaviour**, capturing short-term oscillations without representing the underlying long-term structure. The **Spline** and **Segmented Linear** alternatives fail to adequately reproduce the characteristic rise–saturation–decline profile expected from natural gas usage under increasing renewable penetration and vehicle electrification. The **Bi-Logistic model clearly yields the best performance**, achieving the highest CV-Adjusted R^2 value of **0.996**, accurately representing both historical growth and the projected post-2040 downturn.

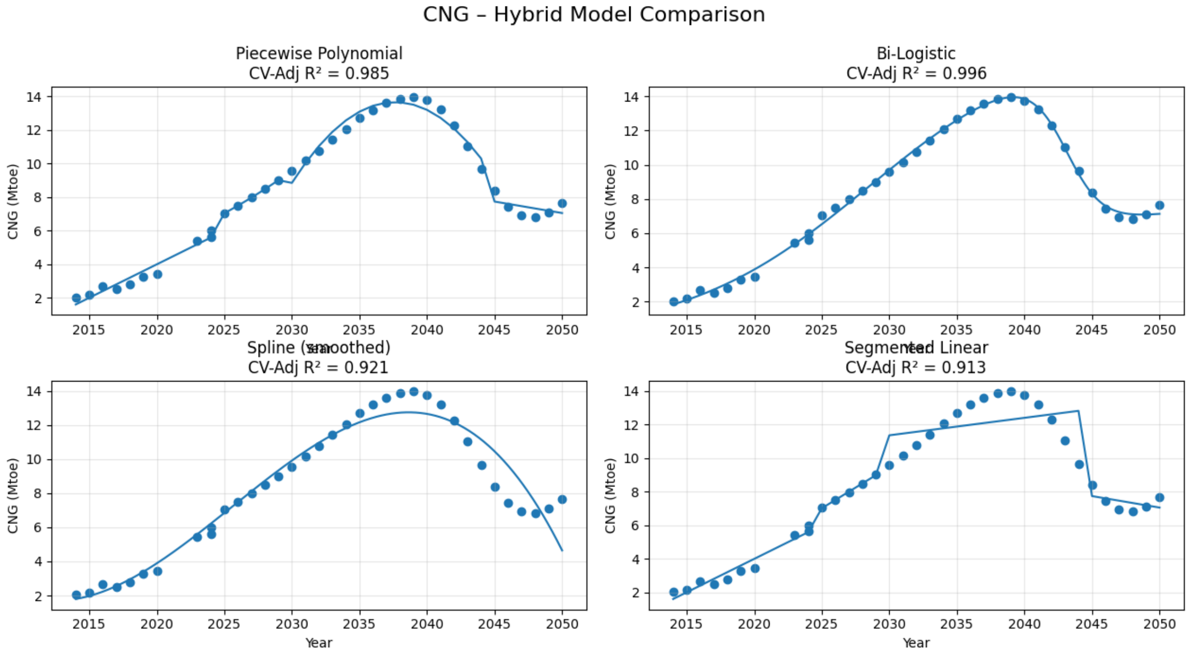


Figure 15: Hybrid Curve Fitting Results for CNG Consumption in India

The fitted Bi-Logistic equation for CNG consumption, using the optimised parameters obtained from the curve-fitting process, is given by:

$$E(t) = \frac{17.4911}{1+e^{-0.14736(t-2014)}} - \frac{9.7168}{1+e^{-0.72435(t-2039)}},$$

where t denotes calendar year. Here, $t_1 = 2014$ marks the onset of accelerated adoption of CNG in Indian road transport, while $t_2 = 2039$ represents the transition point at which electrification and low-carbon alternatives drive demand reversal.

7.6 Transport Mtoe and CO_2 emissions Correlation

The energy trajectories from the previous section have been converted into CO_2 emissions using constant, fuel–specific emission factors $\mathbf{EF_f}$ (in $MtCO_2$/Mtoe). For each fuel or carrier f and year t, the resulting emissions are:

$$\text{Emissions}_{f,t} = \text{Energy}_{f,t} \times EF_f. \tag{8}$$

Table 6 summarises the emission factors used.

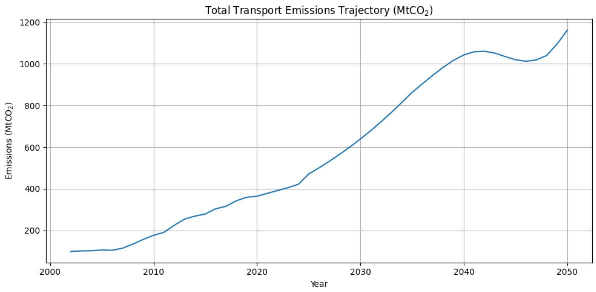
Table 6: Emission factors used to convert fuel use (Mtoe) into CO_2 emissions ($MtCO_2$).

Fuel / carrier	Emission factor EF_f [$MtCO_2$/Mtoe]	Source
Coal-based grid electricity	4.02	[23]
Oil + gas (grid)	3.17	[24]
Nuclear	0.012	[25]
Hydro	0.024	[25]
Renewable electricity (RES)	0.030	[26]
Road ethanol	1.50	[27]
Road CNG	2.80	[27]
Petroleum products (road/rail/air/ship)	3.10	[24, 23]

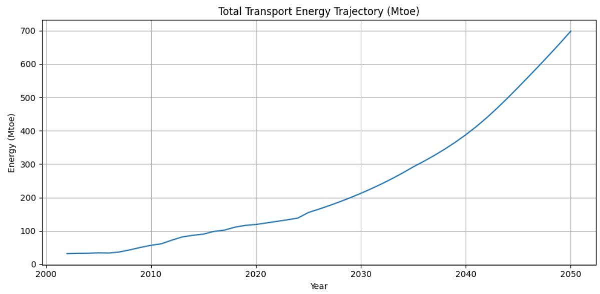
A critical implication of this formulation is that fuels with very low emission factors—notably nuclear, hydro and renewable electricity—retain their full contribution in the energy (Mtoe) plots, but appear much smaller in the emissions plots because each unit of energy is multiplied by a **very small EF_f**. In stacked area terms, **the renewable bands are therefore visibly compressed in the CO_2 figures compared to the Mtoe figures**, even though the underlying energy deployment is identical. **This is not a data error; it is a direct and expected consequence of the decarbonisation of the energy mix**.

Finally, all curves show a modest increase or kink close to 2050 in both energy and emissions. This should *not* be over–interpreted. The trajectory is a synthetic forecast constructed from a combination of short–, medium– and long–term policy and planning targets. By construction, many short- and medium–term targets have formally "expired" by 2050, and no new targets beyond current announcements are assumed to replace them. **In a real policy context, new decarbonisation goals will inevitably be introduced** and will overlap this period. The slight end–point increase therefore reflects **a limitation of the projection method, not an anticipated reversal of the transition**.

7.6.1 Total transport trends: emissions vs energy



(a) Total transport CO_2 emissions.

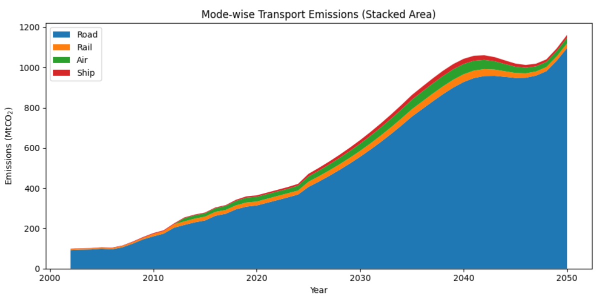


(b) Total transport final energy demand.

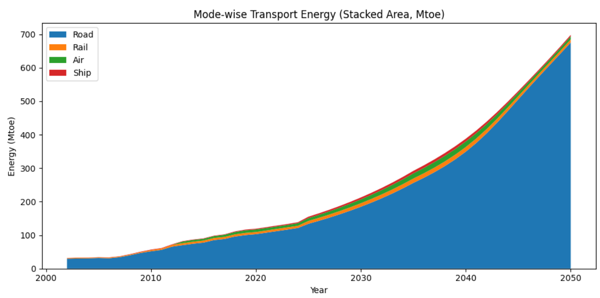
Figure 16: Total transport trajectories in (a) CO_2 emissions and (b) final energy (Mtoe).

Figure 16 compares the aggregate transport pathway in emissions ($MtCO_2$) and in final energy demand (Mtoe). The Mtoe curve (Figure 16b) grows almost monotonically as overall mobility demand and electrification increase over time. In contrast, the emissions curve (Figure 16a) increases at first but eventually peaks and begins to flatten as the fuel mix shifts towards lower–carbon carriers (CNG, ethanol, grid electricity, and later RES–rich electricity) and as conventional road modes become more efficient. On a first glance the continued rise in total energy might appear incompatible with climate goals, but the divergence between Figures 16a and 16b is exactly the signature of a transition: energy services continue to grow, while emissions per unit energy (the system–wide carbon intensity) decrease.

7.6.2 Mode-wise comparison: emissions vs energy



(a) Mode-wise CO_2 emissions.

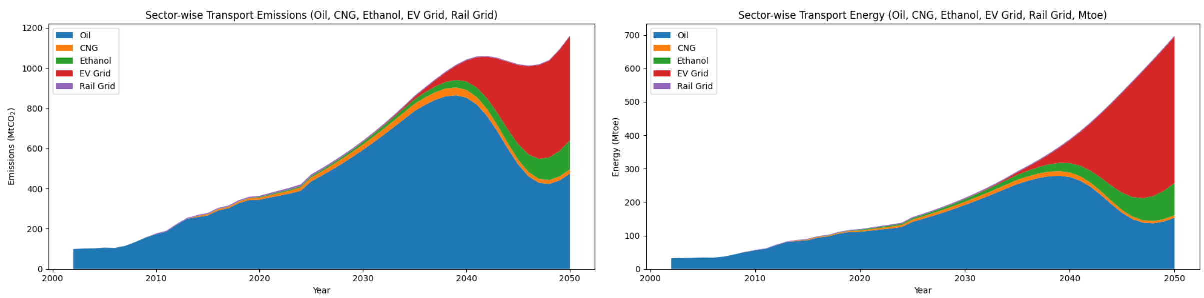


(b) Mode-wise final energy demand.

Figure 17: Mode-wise transport trajectories in (a) CO_2 emissions and (b) final energy (Mtoe).

The mode–wise stacked areas in Figure 17 show that road transport dominates both energy use and emissions throughout the horizon, as expected for an Indian context with high road mode shares. In energy terms (Figure 17b), road demand rises sharply with only a modest contribution from rail, air and shipping. In the emissions plot (Figure 17a), however, the growth of road emissions slows and eventually flattens despite rising road energy. This is driven by three mechanisms already embedded in the scenario: (i) efficiency improvements in conventional internal combustion road vehicles, (ii) gradual penetration of CNG and ethanol blends, and (iii) increasing electrification of road transport, which shifts a portion of the emissions from tailpipe to the power sector. Rail emissions grow slowly and remain a small fraction of the total, reflecting both higher baseline efficiency and rapid electrification of the rail network. The fact that the aggregate curve in Figure 16a is less steep than in Figure 16b confirms that decarbonisation, rather than demand suppression, is the main driver of mitigation here.

7.6.3 Sector-wise fuel shift: emissions vs energy



(a) Emissions by fuel / carrier.

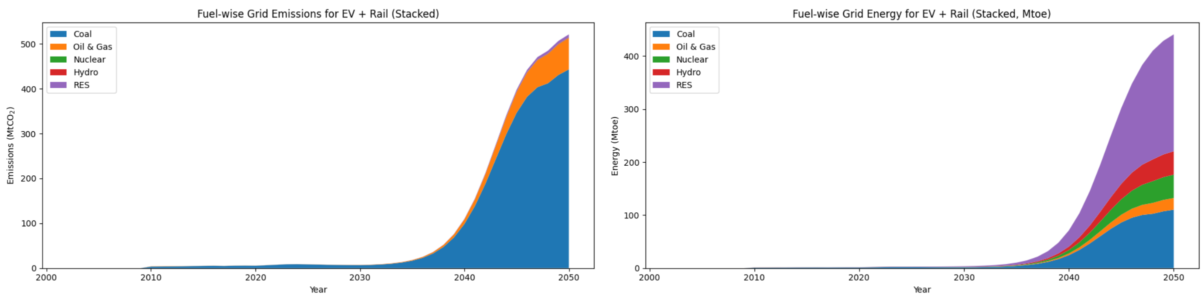
(b) Final energy by fuel / carrier.

Figure 18: Sector-wise breakdown of transport in (a) CO_2 emissions and (b) final energy demand.

The sector–wise comparison in Figure 18 makes the impact of emission factors particularly clear. In the Mtoe plot (Figure 18b), the contribution from the EV grid and, later, from the rail grid grows substantially, and by the 2040s these electric carriers account for a sizeable fraction of total transport energy. Oil demand grows initially and then gradually declines as electrification and alternative fuels penetrate.

In the emissions plot (Figure 18a), oil remains visually dominant for much longer, and the relative share of renewable and low–carbon electricity appears much smaller. This is *solely* because of the multiplication by the emission factors in Table 6. Coal and oil have emission factors of 4.02 and 3.10 $MtCO_2$/Mtoe, respectively, while renewable electricity has an effective factor of only 0.03 $MtCO_2$/Mtoe. When energies are converted to emissions, each unit of renewable electricity contributes roughly two orders of magnitude less to the stacked area than a unit of coal. Therefore, even a large band of RES in the Mtoe figure is compressed into a very thin layer in the emissions figure. This is not a failure of the renewable transition; rather, it quantitatively confirms that shifting from oil and coal to low–carbon electricity dramatically reduces total CO_2 even if the absolute energy supplied by renewables becomes very large.

7.6.4 Grid supply mix for EV + Rail: emissions vs energy



(a) Grid CO_2 emissions by fuel (EV + rail).

(b) Grid energy by fuel (EV + rail).

Figure 19: Fuel-wise grid mix supplying EVs and electrified rail, shown in (a) emissions and (b) energy terms.

The grid fuel–mix comparison in Figure 19 focuses on the upstream electricity supply for EVs and electrified rail. In Mtoe terms (Figure 19b), coal remains important in the near term but its relative share is progressively displaced by hydro, nuclear and especially renewables after 2030, consistent with announced capacity addition targets. The total grid energy dedicated to transport rises steeply as EV and rail electrification scale up.

In the emissions view (Figure 19a), coal dominates the stacked area during the early decades because of its very high emission factor. However, as the renewable and low–carbon share of generation increases, the coal band stops growing and eventually flattens even while total grid energy continues to rise. The low–carbon carriers (hydro, nuclear and RES) occupy a much smaller vertical span in the emissions plot than in the Mtoe plot for the same reason discussed above: their specific emissions per unit energy are small. The combined effect is a progressive decoupling between electricity supplied to transport and the associated CO_2 footprint: more electrified kilometres are delivered per tonne of CO_2 over time.

Overall, the system is following a realistic transition pathway where (i) demand and activity continue to grow from a low baseline, (ii) structural change in modes and fuels gradually shifts energy from oil and coal to lower–carbon carriers, and (iii) the resulting reductions in carbon intensity precisely explain the divergence between the Mtoe and CO_2 views.

7.7 Scenario Modelling and Interpretation of Results

A comparative scenario analysis was implemented to evaluate the sensitivity of long-term transport energy and emissions outcomes to differing rates of technological adoption and fuel substitution. Three system-level scenarios were constructed for 2024–2050: **Business-as-Usual (BAU)**, **Accelerated Transition**, and **Conservative Growth** across the five major transport energy categories, and subsequently aggregated to compute total transport final energy and associated CO2 emissions.

Rationale

The use of scenario-based divergence is consistent with established energy system planning practices and national transition modelling (e.g., IPCC, IEA) which assess uncertainty through controlled sensitivity bound adjustments rather than isolated point forecasts [28, 29]. The $\pm 10\%$ variation applied here represents a commonly used uncertainty margin range for long-term sector projections in literature ($\pm 10-20\%$ is typical) [30], enabling transparent comparison without imposing extreme or speculative behaviour.

To avoid unrealistic discontinuities often created by static multipliers, a **smooth linear scaling function** was applied from 2024 to 2050:

$$Scale = \frac{(year - 2024)}{(2050 - 2024)}$$

and scenario values were generated as:

$$Value_{Acc} = BAU \times (1 \pm 0.10 \times Scale), \qquad Value_{Cons} = BAU \times (1 \mp 0.10 \times Scale).$$

Accelerated trajectories increase clean fuels (EVs, ethanol) and reduce fossil fuels (oil, CNG), while Conservative produces the opposite trend. Rail remains constant, reflecting saturated electrification. Total emissions were computed using:

$$E_{fuel} = Activity \times EF_{fuel},$$

with emission factors drawn from international lifecycle datasets [29].

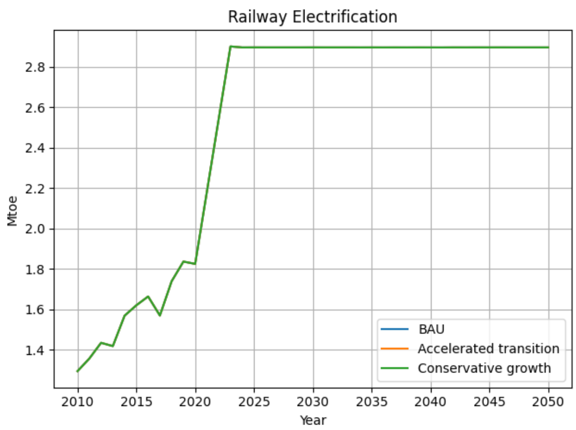
Interpretation of Results

EV and ethanol consumption increase sharply under the Accelerated pathway, while oil and CNG peak around 2040 and decline fastest under Accelerated, consistent with substitution effects already embedded in the forecasting methodology. Rail stabilises due to infrastructural saturation.

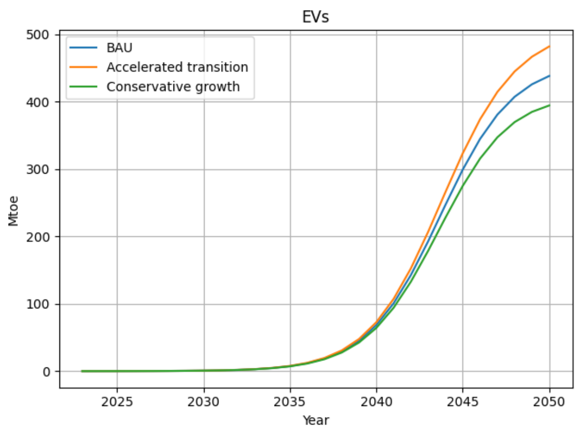
Total transport energy demand increases across all scenarios due to rising mobility demand, but diverges as:

$$\text{Conservative} > \text{BAU} > \text{Accelerated}$$

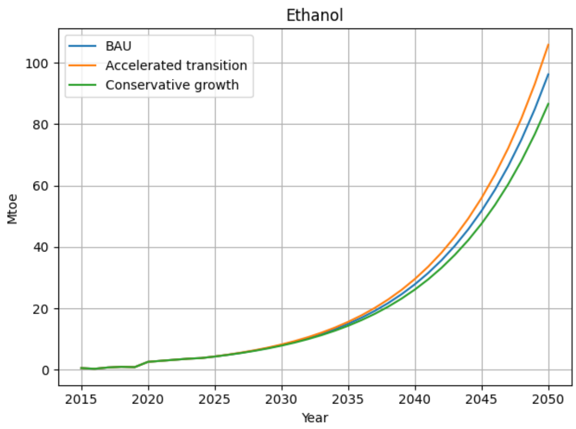
reflecting efficiency and electrification effects. Total CO2 emissions reach approximately **1280 Mt**, **1150 Mt**, and **1030 Mt** under Conservative, BAU and Accelerated respectively in 2050. The $\sim 10\%$ reduction achieved under Accelerated relative to BAU demonstrates the material mitigation potential of rapid electrification and alternative fuels, aligning with global transport decarbonisation findings [28].



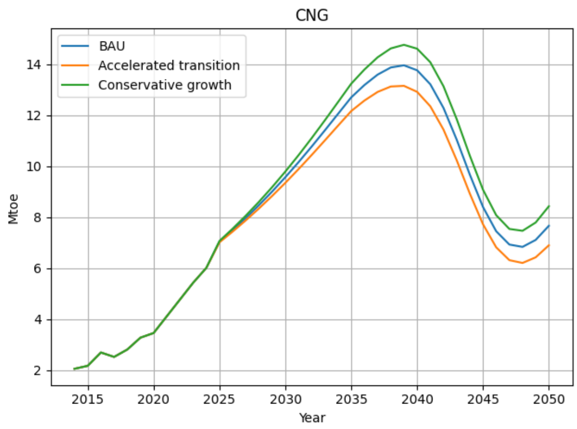
(a) Railway Electrification – Scenario comparison



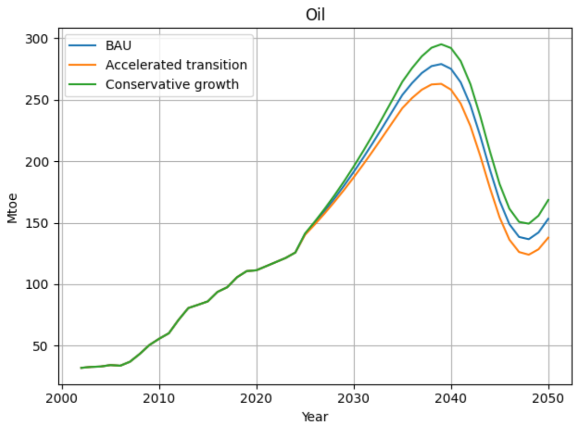
(b) EV Energy Demand – Scenario comparison



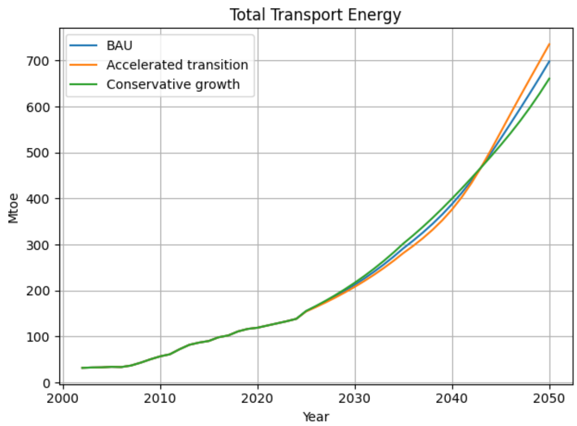
(a) Ethanol Demand – Scenario comparison



(b) CNG Consumption – Scenario comparison



(a) Oil Consumption – Scenario comparison



(b) Total Transport Energy – Scenario comparison

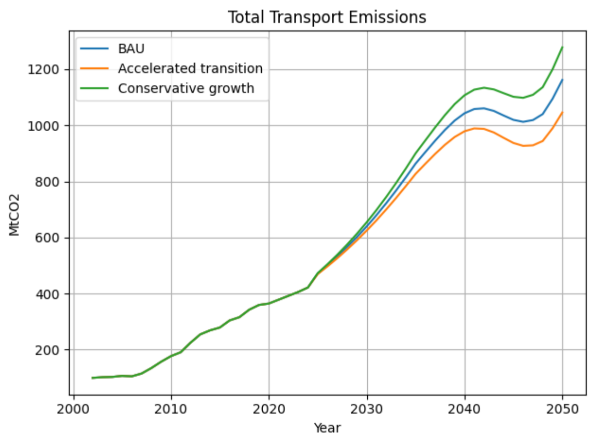


Figure 23: Total Transport CO_2 Emissions – Scenario comparison

8 Test Matrix

Table 7: Test Matrix: Summary of methodologies and rationale used in the transport energy forecasting model.

Component	Methodology	Key Data / Basis	Rationale
GDP–Driven Transport Demand	Exponential decay model for Energy Intensity and GDP-linked transport energy projection: $ED_t = GDP_t \times EI_t$	World Bank GDP; IEA Transport Energy; EI fit (2009–2024), decay rate 1.794%	Links macroeconomic growth to transport energy without assuming constant intensity or linear trend.
Total Final Energy Mix Alignment	Linear interpolation of TFEC composition between policy anchor years to 2047	IEA Balances (2000–2021), assumed TFEC mix targets for 2030 and 2047	Ensures realistic forward allocation of fuels for attribution and emissions modelling.
Electric Vehicles (EVs)	Target–based CAGR and logistic S–curve adoption (saturation beyond 2045)	NITI EV penetration targets; vehicle population; BEE electricity data	Avoids distorted 127% historical CAGR; captures real saturation.
EV Supply Attribution	Constant Demand/Supply ratio applied to total electricity generation	T&D ratio 0.889; national electricity production data	Reflects stable grid efficiency and energy accounting consistency.
EV Primary Fuel Attribution	Proportional allocation using projected national generation mix	National decarbonisation pathway (2030, 2047)	Enables fuel-wise electricity attribution for emissions computation.
Railways Electrification	Piecewise Linear + Logistic hybrid curve fitting with stabilisation post 2026	98% electrification (2024); 100% target (2026); CV–Adj $R^2 = 0.9801$	Captures growth–acceleration–saturation transition; avoids unrealistic continued growth.

Table 7 (continued)

Component	Methodology	Key Data / Basis	Rationale
Ethanol	Target–based CAGR derived from E20 (2025) and E25 (2030) blending requirements	MoPNG blending targets; petrol demand projections	Historical CAGR (23.76%) unrealistic; target-based growth yields policy-consistent trajectory.
Oil & CNG Combined Projection	Residual displacement model: Oil+CNG = Total Energy – (EV + Rail + Ethanol)	GDP–EI forecast for total demand; historical baseline levels (2024)	Captures substitution instead of independent growth and prevents double counting.
Oil and CNG Split	Fixed 20:1 split from 2024 baseline	2024 values: Oil 5266.43 PJ; CNG 251.49 PJ	Maintains realistic proportions in absence of policy-driven divergence.
Oil Subsectors (Road, Rail, Aviation, Shipping)	Best–performing Bi–Logistic curve fitting using CV–Adjusted R^2 across alternatives	Historical modal shares (87/4/6/3%); hybrid curve evaluation	Captures growth–peak–decline behaviour aligned with transition expectations.
CNG Curve Fit	Bi–Logistic regression	Historical natural gas consumption and transport share	Best fit (CV–Adj $R^2 = 0.996$); represents saturation and decline.
Emissions Modelling	Activity-based model: $Emissions_{f,t} = Energy_{f,t} \times EF_f$	Fuel-wise EF factors (Table 6); electricity fuel attribution	Converts energy forecasts to CO_2 results for scenario comparison.
Scenario Divergence (BAU / Acc / Cons)	Linear scaling from 2024–2050 applying $\pm 10\%$ controlled deviation	Common sensitivity bounds 10–20% in national energy modelling literature	Explores policy uncertainty smoothly without abrupt jumps or speculative extremes.

9 Results and Discussion

This section synthesises the outcomes of the integrated modelling framework developed across the report, combining historical analysis, GDP-linked transport energy forecasting, fuel-wise projections, curve-fitting-based subsector modelling, electricity attribution, and emissions translation. The results highlight the structural transformation underway in India's transport energy landscape and quantify its implications for long-term decarbonisation.

9.1 Historical and GDP–Driven Demand Trends

The projections derived from the GDP–Energy Intensity formulation (Section 5) show a steady rise in total transport energy demand from **125 Mtoe in 2024 to 192 Mtoe by 2050** (Figure 16b). While GDP increases sharply over the same period, the energy intensity trajectory declines at **1.794% annually**, producing visible **decoupling of energy from economic growth**. This establishes a key structural finding: future reductions in transport emissions will rely more on **efficiency and fuel switching** than on demand suppression.

9.2 Fuel–Wise Composition and Transition Signals

The historical fuel mix demonstrates the overwhelming dominance of **oil**, representing **over 90% of transport energy in 2023**. However, the smooth TFEC-aligned composition trajectory (Figure 18) shows a gradual erosion of oil's share as EVs, rail electrification, ethanol, and eventually modern renewables expand. Although the absolute value of petroleum consumption continues to rise from **112 Mtoe in 2024 to 276 Mtoe in 2038**, it subsequently peaks and declines to **112 Mtoe by 2050**, reflecting displacement effects. This observed peak–decline trajectory aligns quantitatively with national decarbonisation pathways and historical peak-oil models.

9.3 Alternative Fuels: EVs, Rail Electrification, and Ethanol

The EV sector exhibits the fastest rise across all alternative fuels, with energy demand increasing from **1.8 Mtoe in 2024** to **34 Mtoe by 2050**, driven initially by a **59.99% CAGR** and later by logistic saturation behaviour (Figure 20b). Rail traction energy stabilises post-electrification at **10.1 Mtoe**, confirming its role as a steady low-carbon backbone rather than a growth market. Ethanol grows from **4.5 Mtoe in 2024** to **26–27 Mtoe by 2050**, consistent with blending mandates.

A consistent insight is that while these fuels remain smaller in magnitude compared to oil, their slope behaviour is economically decisive: **their growth offsets the decline in oil and moderates system-wide emissions without suppressing activity**.

9.4 Oil and CNG Transition Dynamics

The bi-logistic modelling of oil subsectors (Figure 13) reveals distinct transition timings: **road and aviation segments exhibit the earliest inflection**, whereas rail and shipping decline more gradually due to specialised use. CNG demand follows a similar growth-saturation-decline structure peaking around **2039**, reaching **15 Mtoe** before falling to **8–9 Mtoe** by 2050 (Figure 14), reflecting competitive pressure from electrification and ethanol.

The preservation of the historical **20:1 oil–CNG ratio** enables credible internal allocation of substitution effects, preventing over-estimation observed in pure CAGR methods (Figures 11–14).

9.5 Energy–Emissions Divergence

Although total energy grows steadily, **CO_2 emissions do not follow the same trajectory**. As shown in Figure 16, emissions rise initially from **1100 $MtCO_2$ in 2024 to 1170 $MtCO_2$ in 2036**, before flattening due to falling carbon intensity of energy supply, reaching **1150 $MtCO_2$ by 2050** under the BAU trajectory. The divergence between Figures 16a and 16b is directly attributable to:

1. increased electrification of transport,
2. declining grid emission factor,
3. fuel substitution effects,
4. efficiency improvements in ICE vehicles.

The compression of renewable and nuclear bands in emission figures quantitatively illustrates the leverage of low-carbon fuels: each Mtoe of renewables produces **two orders of magnitude less CO_2** than coal-grid electricity.

9.6 Scenario Comparison and System-Level Insights

Across the Conservative, BAU and Accelerated pathways (Figures 20a–23), trajectories diverge smoothly from 2024 onward due to the progressive $\pm 10\%$ scaling applied. The energy demand gap between Conservative and Accelerated widens to **14 Mtoe by 2050**, while total emissions diverge to **1280, 1150 and 1030 $MtCO_2$** respectively. The **10.4% reduction** achieved under Accelerated compared to BAU demonstrates that measurable emissions mitigation arises primarily through **faster electrification and renewable expansion**, not reduced mobility.

A key outcome is that rail saturation removes it from sensitivity space, highlighting road-mode electrification as the single most impactful transition lever.

Overall, the system demonstrates a genuine structural transition: energy demand continues to expand with economic growth, but emissions flatten and begin decline due to efficiency improvements and low-carbon carriers.

10 Summary and New Observations

This study demonstrates that transport energy demand in India will continue to rise significantly through 2050, but the composition of this energy is undergoing a major transformation. While petroleum remains dominant in absolute terms, its peak and subsequent decline post-2038, combined with the rapid growth of EVs and ethanol and stabilising rail electrification, signal the beginning of a systemic transition. The divergence between energy and emissions trajectories confirms that **real decarbonisation is occurring without suppressing mobility growth**.

The modelling reveals that:

- **GDP and transport energy demand are progressively decoupling**, driven by efficiency gains.
- **Electrification is the strongest lever** for emissions reduction, amplified by renewable grid growth.
- **Bi-logistic behaviour captures transition dynamics more accurately** than traditional CAGR, avoiding unrealistic exponential growth forecasts.

- **Fuel substitution effects must be modelled explicitly**; independent projections significantly over-predict demand.
- **EVs and ethanol growth meaningfully compress oil demand despite lower absolute magnitudes**.
- **Scenario divergence quantifies policy impact**, with **10% mitigation potential** between Conservative and Accelerated outcomes by 2050.

From a policy and planning perspective, the results emphasise that:

1. grid decarbonisation can yield large emissions reductions even with growing electricity demand,
2. managing the pace of EV charging infrastructure and biofuel production is crucial to sustain system balance,
3. long-term planning should prioritise renewable integration and resilient supply chains rather than demand reduction.

In conclusion, India's transport system is entering a transition characterised by growth in economic activity coupled with declining carbon intensity. The results presented here offer a quantitative foundation for future extensions incorporating cost, technology uncertainty, and policy response simulation. The next stage of this work will integrate multi-dimensional sustainability metrics, enabling a comprehensive roadmap to align transport development with national Net-Zero objectives.

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Appendix

Table A1. GDP–Transport Energy–Energy Intensity Dataset (2002–2050)

Year	GDP (T USD)	TED (Mtoe)	EI (Mtoe/T USD)
2002	0.485	31.916	65.747
2003	0.515	32.976	64.039
2004	0.608	33.645	55.364
2005	0.709	36.477	51.437
2006	0.820	38.956	47.485
2007	0.940	40.794	43.386
2008	1.217	48.172	39.591
2009	1.199	54.748	45.665
2010	1.342	59.987	44.703
2011	1.676	64.946	38.760
2012	1.823	70.526	38.686
2013	1.828	74.520	40.774
2014	1.857	76.266	41.076
2015	2.039	79.717	39.093
2016	2.104	87.936	41.803
2017	2.295	92.324	40.232
2018	2.651	100.536	37.917
2019	2.703	105.693	39.103
2020	2.836	107.414	37.880
2021	2.675	94.425	35.301
2022	3.167	105.027	33.160
2023	3.346	120.959	36.149
2024	3.638	125.010	34.358
2025	3.913	132.061	33.752
2026	4.167	138.166	33.157
2027	4.438	144.554	32.573
2028	4.726	151.236	31.999
2029	5.034	158.228	31.435
2030	5.361	165.543	30.881
2031	5.709	173.196	30.336
2032	6.080	181.202	29.802
2033	6.475	189.579	29.277
2034	6.896	198.344	28.761
2035	7.345	207.513	28.254
2036	7.749	215.067	27.756
2037	8.175	222.897	27.266
2038	8.624	231.012	26.786
2039	9.099	239.422	26.314
2040	9.599	248.138	25.850
2041	10.127	257.172	25.394
2042	10.684	266.534	24.947
2043	11.272	276.238	24.507
2044	11.892	286.294	24.075
2045	12.546	296.717	23.651
2046	13.236	307.519	23.234
2047	13.964	318.715	22.825
2048	14.732	330.318	22.422
2049	15.542	342.343	22.027
2050	16.397	354.807	21.639

Table A2. Total Final Energy Mix – Historical Data & Projection for India (2002–2050)

Year	Coal	Oil+Gas	Trad. Biomass	Modern RES	Other	TFEC (Mtoe)
2002	10.532	9.575	8.298	0.319	2.872	31.916
2003	11.139	9.929	8.317	0.366	2.932	32.976
2004	11.628	10.168	8.223	0.410	2.954	33.645
2005	12.887	11.063	8.634	0.485	3.163	36.477

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2006	14.067	11.858	8.917	0.561	3.335	38.956
2007	15.049	12.467	9.020	0.636	3.443	40.794
2008	18.146	14.774	10.275	0.804	4.013	48.172
2009	21.045	16.851	11.256	0.975	4.500	54.748
2010	23.527	18.530	11.865	1.134	4.865	59.987
2011	25.979	20.133	12.340	1.299	5.196	64.946
2012	28.521	21.941	12.850	1.488	5.720	70.526
2013	30.471	23.265	12.996	1.654	6.126	74.520
2014	31.521	23.894	12.714	1.777	6.353	76.266
2015	33.306	25.063	12.667	1.945	6.728	79.717
2016	37.126	27.753	13.287	2.251	7.527	87.936
2017	39.395	29.239	13.230	2.465	8.005	92.324
2018	43.341	31.950	13.633	2.795	8.827	100.536
2019	46.040	33.706	13.508	3.055	9.396	105.693
2020	47.262	34.372	12.890	3.222	9.667	107.414
2021	41.547	29.272	12.275	2.833	8.498	94.425
2022	47.472	32.768	11.973	3.361	9.452	105.027
2023	56.125	37.981	11.854	4.113	10.886	120.959
2024	59.505	39.503	10.251	4.500	11.251	125.010
2025	64.446	41.996	8.716	5.018	11.886	132.061
2026	69.083	44.213	6.908	5.527	12.435	138.166
2027	70.831	45.679	6.649	8.384	13.010	144.554
2028	72.593	47.186	6.352	11.494	13.611	151.236
2029	74.367	48.734	6.013	14.873	14.241	158.228
2030	76.150	50.325	5.628	18.541	14.899	165.543
2031	77.938	51.959	5.196	22.515	15.588	173.196
2032	79.367	53.274	5.436	26.818	16.308	181.202
2033	80.761	54.599	5.687	31.281	17.062	189.579
2034	82.313	55.933	5.950	36.297	17.851	198.344
2035	83.628	57.274	6.225	41.710	18.676	207.513
2036	84.091	58.283	6.452	46.885	19.356	215.067
2037	84.478	59.068	6.687	52.604	20.061	222.897
2038	85.012	59.832	6.930	58.677	20.791	231.012
2039	85.234	60.574	7.183	64.883	21.548	239.422
2040	85.360	61.290	7.444	71.712	22.332	248.138
2041	85.381	61.978	7.715	78.695	23.145	257.172
2042	85.558	62.636	7.996	86.357	23.988	266.534

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2043	85.357	63.258	8.287	94.473	24.861	276.238
2044	85.029	64.130	8.589	102.780	25.767	286.294
2045	84.564	64.684	8.902	111.862	26.705	296.717
2046	84.260	65.194	9.226	121.470	27.677	307.519
2047	83.503	65.655	9.561	131.311	28.684	318.715
2048	82.579	66.064	9.910	142.037	29.729	330.318
2049	81.478	66.415	10.270	153.370	30.811	342.343
2050	80.186	66.704	10.644	164.985	31.933	354.807

Table B1. Projected EV Energy Demand and Supply (Mtoe) (2023–2050)

Year	**Demand (Mtoe)**	**Supply (Mtoe)**	**Ratio**
2023	0.018	0.020	1.123
2024	0.040	0.045	1.124
2025	0.059	0.066	1.124
2026	0.095	0.106	1.124
2027	0.152	0.170	1.124
2028	0.243	0.274	1.124
2029	0.391	0.439	1.124
2030	0.627	0.704	1.124
2031	1.005	1.130	1.124
2032	1.611	1.811	1.124
2033	2.580	2.900	1.124
2034	4.127	4.639	1.124
2035	6.585	7.401	1.124
2036	10.469	11.768	1.124
2037	16.551	18.603	1.124
2038	25.935	29.152	1.124
2039	40.099	45.072	1.124
2040	60.771	68.308	1.124
2041	89.518	100.621	1.124
2042	126.915	142.656	1.124
2043	171.557	192.835	1.124
2044	219.694	246.943	1.124
2045	266.225	299.245	1.124
2046	306.687	344.724	1.124
2047	338.757	380.772	1.124
2048	362.360	407.303	1.124
2049	378.800	425.782	1.124
2050	389.817	438.165	1.124

Table B2. Source-wise split of grid electricity supply required for EVs (2023-2050)

Year	**Coal** (Mtoe)	**Oil & Gas** (Mtoe)	**Nuclear** (Mtoe)	**Hydro** (Mtoe)	**RES** (Mtoe)	**Total** (Mtoe)
2023	0.014	0.000	0.001	0.002	0.002	0.020
2024	0.034	0.001	0.001	0.003	0.006	0.045
2025	0.049	0.001	0.002	0.005	0.009	0.066
2026	0.074	0.002	0.004	0.008	0.018	0.106
2027	0.110	0.004	0.008	0.013	0.035	0.170
2028	0.164	0.008	0.015	0.022	0.066	0.274
2029	0.241	0.014	0.027	0.035	0.121	0.439

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Year	Coal	Oil & Gas	Nuclear	Hydro	RES	Total
2030	0.352	0.026	0.050	0.056	0.221	0.704
2031	0.508	0.045	0.090	0.090	0.395	1.130
2032	0.794	0.074	0.147	0.147	0.650	1.811
2033	1.237	0.119	0.239	0.239	1.066	2.900
2034	1.924	0.194	0.387	0.387	1.746	4.638
2035	2.982	0.313	0.627	0.627	2.852	7.401
2036	4.603	0.505	1.011	1.011	4.638	11.767
2037	7.058	0.810	1.620	1.620	7.496	18.603
2038	10.718	1.286	2.572	2.572	12.004	29.152
2039	16.040	2.015	4.030	4.030	18.957	45.072
2040	23.506	3.094	6.188	6.188	29.332	68.308
2041	33.442	4.617	9.233	9.233	44.096	100.621
2042	45.734	6.629	13.259	13.259	63.775	142.656
2043	59.552	9.075	18.149	18.149	87.910	192.835
2044	73.356	11.766	23.532	23.532	114.756	246.943
2045	85.373	14.434	28.868	28.868	141.701	299.245
2046	94.292	16.831	33.661	33.661	166.279	344.724
2047	99.673	18.815	37.629	37.629	187.026	380.772
2048	101.826	20.365	40.730	40.730	203.651	407.303
2049	106.446	21.289	42.578	42.578	212.891	425.782
2050	109.541	21.908	43.817	43.817	219.083	438.165

Table C1. Projected Railway Electrification Energy Demand and Supply (2009-2030)

Year	Demand (Mtoe)	Supply (Mtoe)	Ratio
2009	1.065	1.295	1.216
2010	1.146	1.357	1.185
2011	1.221	1.435	1.175
2012	1.212	1.419	1.170
2013	1.336	1.569	1.174
2014	1.391	1.620	1.165
2015	1.427	1.664	1.166
2016	1.348	1.570	1.164
2017	1.499	1.739	1.160
2018	1.620	1.836	1.134
2019	1.646	1.825	1.108
2020	2.582	2.900	1.123

Year	Demand (Mtoe)	Supply (Mtoe)	Ratio
2023	2.837	3.189	1.124
2024	2.895	3.254	1.124
2025	2.895	3.254	1.124
2026	2.895	3.254	1.124
2027	2.895	3.254	1.124
2028	2.895	3.254	1.124
2029	2.895	3.254	1.124
2030	2.895	3.254	1.124

Table C2. Source-wise split of grid electricity supply required for Railway Electrification (2009-2050)

Year	Coal (Mtoe)	Oil & Gas (Mtoe)	Nuclear (Mtoe)	Hydro (Mtoe)	RES (Mtoe)	Total (Mtoe)
2009	0.874	0.163	0.030	0.168	0.060	1.295
2010	0.902	0.166	0.042	0.184	0.063	1.357
2011	0.953	0.149	0.050	0.203	0.080	1.435
2012	1.017	0.102	0.048	0.167	0.085	1.419
2013	1.139	0.071	0.052	0.206	0.100	1.569
2014	1.225	0.063	0.053	0.189	0.091	1.620
2015	1.276	0.068	0.053	0.173	0.094	1.664
2016	1.200	0.063	0.048	0.156	0.104	1.571
2017	1.316	0.068	0.051	0.168	0.136	1.739
2018	1.368	0.067	0.051	0.181	0.170	1.836
2019	1.311	0.064	0.061	0.206	0.182	1.824
2022	2.119	0.043	0.082	0.291	0.365	2.900
2023	2.161	0.053	0.080	0.224	0.377	2.895
2024	2.018	0.063	0.105	0.225	0.483	2.894
2025	1.875	0.074	0.131	0.226	0.589	2.895
2026	1.732	0.084	0.156	0.228	0.695	2.895
2027	1.589	0.095	0.181	0.229	0.801	2.895
2028	1.446	0.105	0.206	0.230	0.907	2.894
2029	1.303	0.116	0.232	0.232	1.013	2.896
2030	1.269	0.118	0.235	0.235	1.039	2.896
2031	1.234	0.119	0.238	0.238	1.064	2.894
2032	1.200	0.121	0.242	0.242	1.090	2.895
2033	1.166	0.123	0.245	0.245	1.115	2.894
2034	1.132	0.124	0.249	0.249	1.141	2.895
2035	1.098	0.126	0.252	0.252	1.166	2.894
2036	1.064	0.128	0.255	0.255	1.192	2.894
2037	1.030	0.129	0.259	0.259	1.218	2.895
2038	0.996	0.131	0.262	0.262	1.243	2.894
2039	0.962	0.133	0.266	0.266	1.269	2.896
2040	0.928	0.135	0.269	0.269	1.294	2.895
2041	0.894	0.136	0.273	0.273	1.320	2.896
2042	0.860	0.138	0.276	0.276	1.345	2.895

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Year	Coal	Oil & Gas	Nuclear	Hydro	RES	Total
2043	0.826	0.140	0.279	0.279	1.371	2.895
2044	0.792	0.141	0.283	0.283	1.396	2.895
2045	0.758	0.143	0.286	0.286	1.422	2.895
2046	0.724	0.145	0.290	0.290	1.447	2.896
2047	0.724	0.145	0.290	0.290	1.447	2.896
2048	0.724	0.145	0.290	0.290	1.447	2.896
2049	0.724	0.145	0.290	0.290	1.447	2.896
2050	0.724	0.145	0.290	0.290	1.447	2.896

Table D. Projected Ethanol Demand or Supply (2015-2050)

Year	Dem—Sup (Mtoe)	Year	Dem—Sup (Mtoe)
2015	0.562	2034	13.236
2016	0.343	2035	14.983
2017	0.770	2036	16.960
2018	0.978	2037	19.199
2019	0.872	2038	21.733
2020	2.602	2039	24.602
2023	3.618	2040	27.849
2024	3.831	2041	31.525
2025	4.336	2042	35.687
2026	4.909	2043	40.397
2027	5.557	2044	45.730
2028	6.290	2045	51.766
2029	7.121	2046	58.599
2030	8.060	2047	66.334
2031	9.124	2048	75.090
2032	10.329	2049	85.001
2033	11.692	2050	96.221

Table E. Oil Consumption Projection by Subsector (2002–2050)

Year	Road	Rail	Aviation	Shipping
2002	29.671	1.797	0.000	0.520
2003	30.438	1.888	0.000	0.426
2004	30.740	1.843	0.000	0.482
2005	31.916	1.829	0.000	0.508

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2006	30.934	2.113	0.000	0.669
2007	34.173	2.089	0.000	0.696
2008	39.988	2.292	0.000	0.977
2009	46.846	2.442	0.000	1.262
2010	51.810	2.547	0.000	1.286
2011	56.070	2.671	0.000	1.375
2012	65.600	3.992	0.000	1.437
2013	70.071	4.227	5.052	1.248
2014	72.305	4.412	5.276	1.258
2015	74.961	4.456	5.354	1.251
2016	82.117	4.573	5.740	1.305
2017	85.322	4.518	6.386	1.313
2018	92.089	4.613	7.032	1.893
2019	96.028	4.747	7.712	2.153
2020	96.884	4.525	7.669	2.242
2023	107.539	3.820	7.071	2.881
2024	98.022	4.507	6.760	3.380
2025	122.421	5.629	8.443	4.221
2026	130.268	5.989	8.984	4.492
2027	138.576	6.371	9.557	4.778
2028	147.363	6.775	10.163	5.081
2029	156.640	7.202	10.803	5.401
2030	166.408	7.651	11.476	5.738
2031	176.653	8.122	12.183	6.091
2032	187.337	8.613	12.920	6.460
2033	198.380	9.121	13.681	6.841
2034	209.640	9.639	14.458	7.229
2035	220.873	10.155	15.233	7.616
2036	229.279	10.542	15.812	7.906
2037	236.377	10.868	16.302	8.151
2038	241.264	11.093	16.639	8.319
2039	242.725	11.160	16.740	8.370
2040	239.337	11.004	16.506	8.253
2041	229.806	10.566	15.849	7.924
2042	213.661	9.823	14.735	7.368
2043	192.062	8.830	13.246	6.623
2044	168.113	7.729	11.594	5.797

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2045	146.032	6.714	10.071	5.036
2046	129.501	5.954	8.931	4.466
2047	120.421	5.537	8.305	4.152
2048	118.826	5.463	8.195	4.097
2049	123.595	5.683	8.524	4.262
2050	133.237	6.126	9.189	4.594

Table F. CNG Energy Consumption Projection (2014–2050)

Year	CNG (Mtoe)
2014	2.049
2015	2.165
2016	2.687
2017	2.514
2018	2.804
2019	3.268
2020	3.451
2023	5.422
2024	6.006
2024	5.633
2025	7.036
2026	7.487
2027	7.964
2028	8.469
2029	9.002
2030	9.564
2031	10.152
2032	10.766

Year	CNG (Mtoe)
2033	11.401
2034	12.048
2035	12.694
2036	13.177
2037	13.585
2038	13.866
2039	13.950
2040	13.755
2041	13.207
2042	12.279
2043	11.038
2044	9.662
2045	8.393
2046	7.443
2047	6.921
2048	6.829
2049	7.103
2050	7.657