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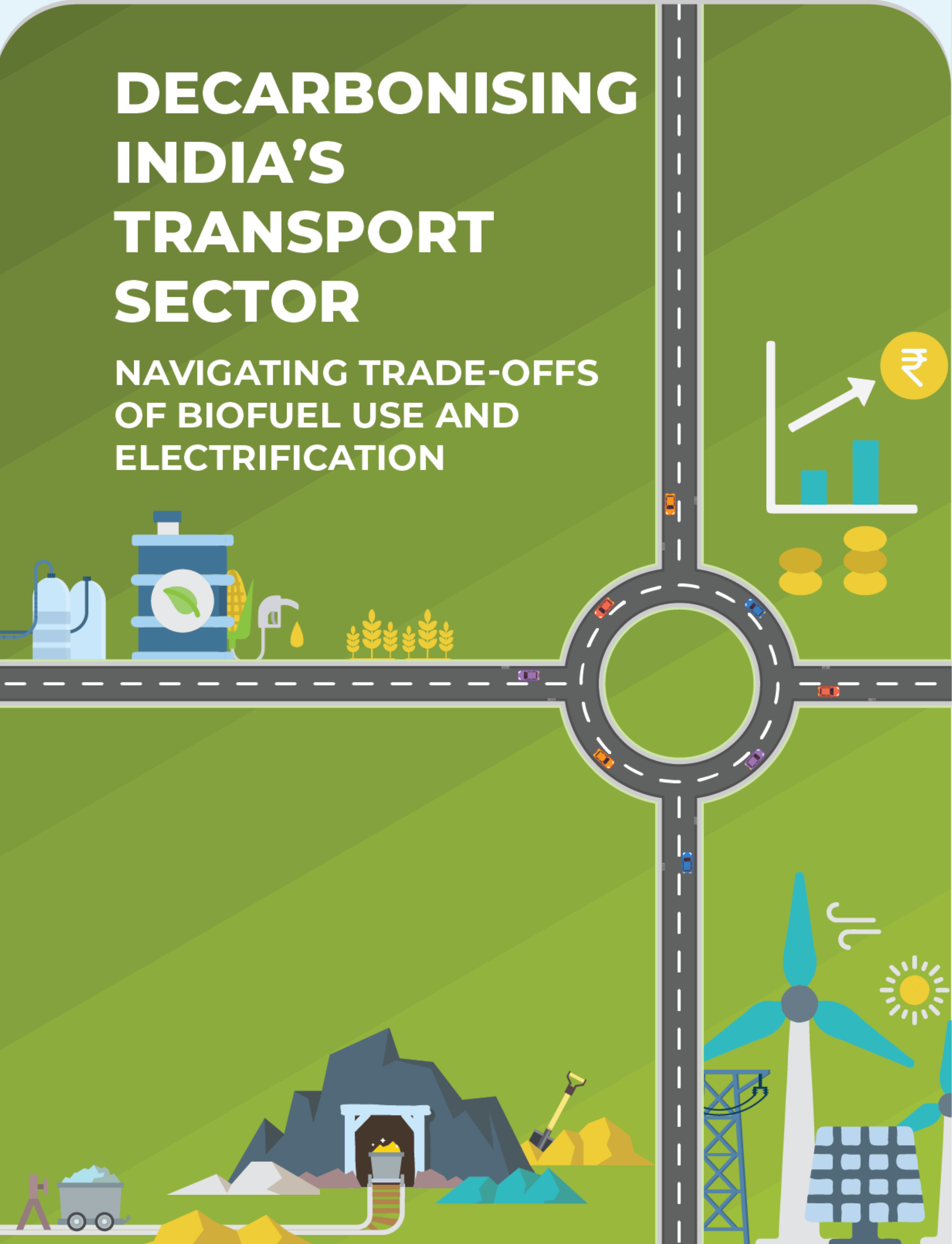
CSTEP

DECARBONISING INDIA'S TRANSPORT SECTOR

NAVIGATING TRADE-OFFS OF BIOFUEL USE AND ELECTRIFICATION



Decarbonising India's Transport Sector: Navigating Trade-offs of Biofuel Use and Electrification

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Executive Summary

Motivation and Objectives

Decarbonising the transport sector is essential not only to achieve the net-zero target but also to improve quality of life through benefits such as better air, reduced traffic-related woes, and urban heat management. Studies have modelled low-carbon strategies for the transport sector in India, with a focus on energy demand and emissions, but the cross-sectoral trade-offs of the strategies, such as their impact on land, water, and material use, are often missed. Further, the ripple effects through the economy or the macroeconomic impacts of the strategies are not well understood in the Indian context. In this study, we aimed to explore the natural resource and macroeconomic implications of two main strategies—biofuel use and electrification—to develop a decarbonisation strategy for the sector with minimal trade-offs.

Our key research questions are as follows:

1) Is reaching and maintaining 20% ethanol blending (E20) in India sustainable, especially in the long term? What are the land, water, and food security implications of using the currently favoured feedstock—sugarcane and maize? How should India pursue biofuels?

2) Electrification of the transport sector is key to reaching net-zero emissions, but it leads to a massive increase in the demand for critical minerals used in batteries. Given that India is import-dependent for most of these minerals and there are uncertainties around their supply, what are the most effective levers to focus on to keep this demand (and therefore our import dependency) on the lower end?

3) Investments in these technologies, including ethanol or electric vehicles (EVs), will have an impact on the overall economy in terms of the growth in the gross domestic product (GDP), employment, and income. What are the impacts?

Approach

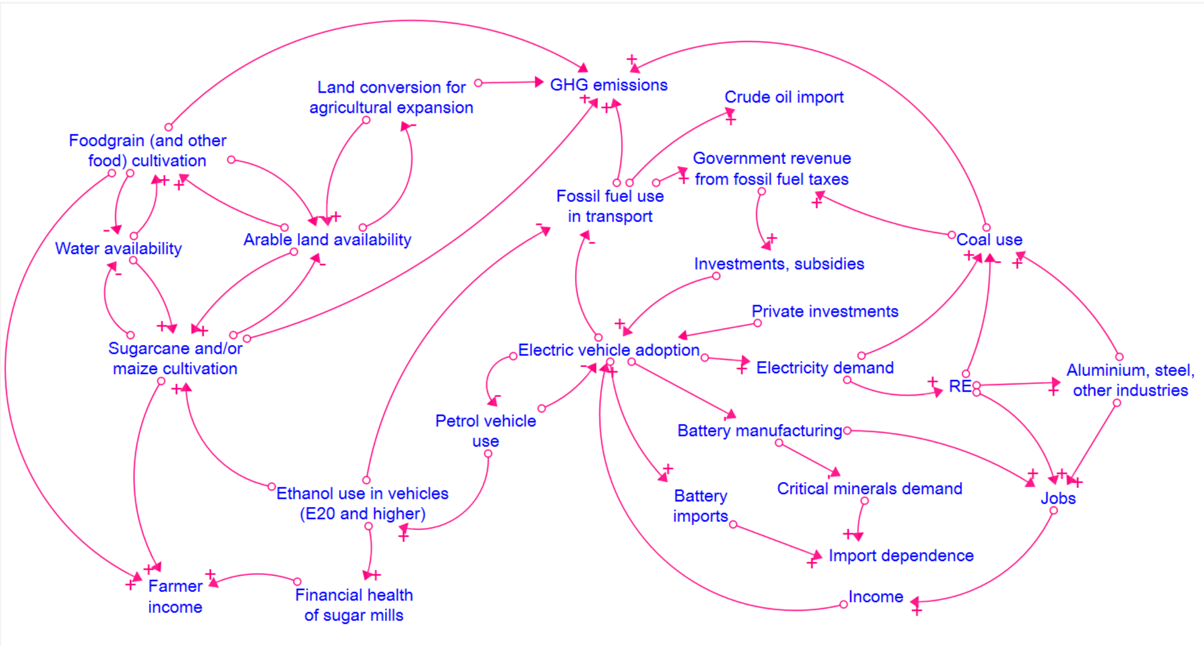
We used two models for this analysis—the Sustainable Alternative Futures for India (SAFARI) and Social Accounting Matrix (SAM)-based multiplier. SAFARI, a system dynamics simulation model, was used to analyse the land, water, and critical minerals implications, while the SAM multiplier was used to determine the macroeconomic implications.

There are several uncertainties involved in modelling for the long term. Simulation models such as SAFARI account for some of these uncertainties through a wide range of exploratory scenarios aligned with Robust Decision-Making (RDM) frameworks used for Decision-Making under Deep Uncertainty (DMDU). The focus is on understanding the trade-offs of various strategies and highlighting the crucial levers for change, rather than aiming to accurately predict the future.

Key findings

Ethanol blending and EV adoption have benefits and trade-offs across the value chain, as captured in Figure ES1. For instance, while ethanol blending can reduce fossil fuel use in the transport sector (and its corresponding GHG emissions), it can lead to increased land-use change emissions. Similarly, while increased EV adoption can reduce crude oil import dependency, it would increase our import dependency for batteries and the critical minerals used in them. Ethanol use might improve the financial health of sugar mills and therefore sugarcane farmers' income, but groundwater depletion due to extensive sugarcane cultivation will negatively impact both sugarcane and other farmers in the long run. More examples depicted in the figure are described in detail below and in the rest of the report.

Figure ES1: Causal loop diagram of the ethanol blending and transport electrification systems



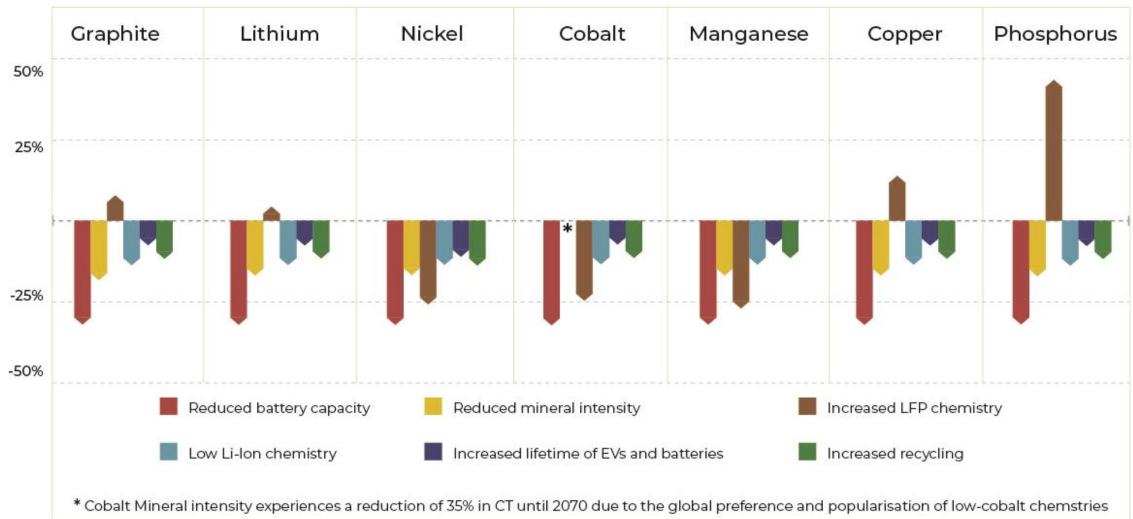
Note: Arrows with a '+' sign denote positive correlation between the connected variables, whereas those with a '-' sign denote inverse correlation.

Achieving ethanol blending of 20% (E20) or more has land-use and groundwater-depletion trade-offs. Reaching and maintaining the E20 by 2025 target leads to an annual ethanol demand of 10 billion litres in 2025, 12 billion litres by 2030, and 20 billion litres by 2050. Meeting this demand, without compromising on food and nutritional security, requires 3.5–10 million hectares of additional land to be brought under cultivation (of maize or sugarcane depending on the scenario) in the coming two decades. This leads to the depletion of fallow land 10–15 years earlier than a regular cropping scenario, increasing pressure on forest land or potential forest land. Groundwater demand for irrigation also increases by up to 30%. Alternatively, this could lead to increased reliance on imports to meet our demands for maize because our current maize production is just enough for our requirements (direct consumption and livestock feed). Further, importing feedstock for ethanol production becomes ironic considering biofuels were meant to bring us closer to *atmanirbharta* (self-reliance).

To sustain E10, on the other hand, is a win–win; the existing sugarcane cultivation is adequate, and no maize is needed. Hence, this scenario avoids the trade-off between food and fuel, the existing vehicles and infrastructure are already E10-compliant, and the surplus ethanol (if any) can be diverted for jet fuel production via the alcohol-to-jet pathway. Our analysis shows that the use of ethanol from this pathway as bio-jet fuel can mitigate up to 500 $MtCO_2e$ in the net-zero year from the hard-to-abate aviation sector. So, higher ethanol blends in India should be pursued only if there is a breakthrough in technology that significantly lowers the overall land and water footprint of ethanol production. Cellulosic (or second generation [2G]) ethanol technology, once commercially viable, could contribute to sustainable ethanol supply, but the contribution will be limited unless we resolve our biomass supply chain challenges.

Electrification of transport has implications on the critical minerals demand, which affects energy security goals because India is currently import-dependent for most of these minerals. A combination of interventions is needed to lower this demand. Individually, most of the levers studied decrease mineral demand, as shown in Figure ES2. This includes a 20% increase in battery recycling, shifting consumer preference towards smaller vehicles (leading to a 20% reduction in battery capacity), reducing mineral intensities by 20%, increasing the lifetime of EVs and batteries by 20%, and improving battery chemistries such as increased share of lithium iron phosphate (LFP) batteries or even a technological shift away from lithium-ion chemistries altogether by 2070, compared with the Current Trajectory (CT). A shift towards LFP battery chemistry has the highest impact in reducing nickel, cobalt, and manganese demands but significantly increases the demand for phosphorus, which India currently imports as fertilisers. In such a scenario, by 2050, phosphorus demand for EVs could increase to 4%–10% of India's current phosphorus imports.

Figure ES2: Impact of levers on cumulative mineral demand by 2070



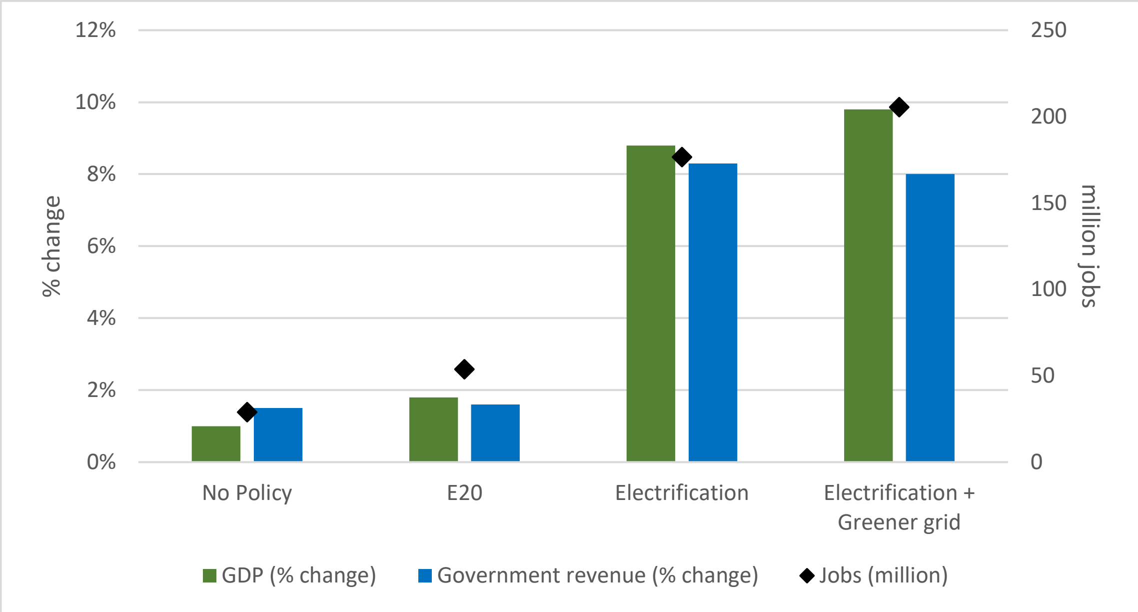
In 2050, the demand for graphite, nickel, and cobalt for EVs (passenger) in a net-zero scenario for India could be 5%–10% of the International Energy Agency's estimate of the global mineral demand for EVs. The demand for copper could be up to 21% of the global demand, whereas lithium demand would likely be less than 5% (Table ES1). The shares in 2070 could be higher depending on the trajectory India takes to reach the net-zero goal. The demand estimates provided are the country's total demand irrespective of whether the batteries are domestically manufactured or imported.

Table ES1: India's critical minerals demand in passenger EVs (domestic + imported batteries) in a net-zero scenario

Mineral	Demand in 2050		Demand in 2070
	Current study (million tonnes)	As a share of IEA's global demand for EVs	Current study (million tonnes)
Graphite	0.32–0.67	5.3%–11%	0.4–1
Lithium	0.03–0.06	2%–4.6%	0.04–0.1
Nickel	0.12–0.26	5%–10%	0.12–0.3
Cobalt	0.02–0.03	5%–9.5%	0.01–0.03
Manganese	0.01–0.03	0.5%–1%	0.01–0.04
Copper	0.20–0.41	9.5%–21%	0.3–0.67
Phosphorus	0.05–0.14	2.4%–6.3%	0.09–0.3

Both ethanol blending and electrification of transport have a positive impact on GDP and employment growth, but electrification has a much larger impact. Figure ES3 shows the comparative growth under different scenarios. Ethanol blending boosts rural employment, primarily in sugarcane farming, while electrification drives economic growth, benefiting industries like manufacturing, power generation, and iron and steel. Both strategies increase government revenue and contribute to GDP growth, with electrification offering more substantial long-term economic benefits. For every INR of EV sold, the GDP increases by INR 12.7, whereas for every INR of ethanol-blended (20%) petrol sold, the GDP increases by INR 3.72. Ethanol blending (with sugarcane as feedstock) is easier to implement than EVs with comparatively lower investments, and rural households are provided with an additional market to sell their crop. However, with EVs, the challenges include the financial burden of developing EV supply chains, setting up charging infrastructure, and providing incentives/subsidies. Government revenue also increases with electrification, despite reduced taxes from the sale of petrol and diesel, because of increased electricity production from coal and therefore the coal cess. Greening the grid may slightly decrease government revenue growth due to reduced coal consumption in power generation. However, this is offset by increased coal demand in industries like steel and aluminium, which must expand to support the growth of renewable energy installations.

Figure ES3: Macroeconomic impacts of ethanol blending and EVs (change from 2018 to 2030)



Roadmap for sustainable decarbonisation of the transport sector

Based on our findings on ethanol blending and EVs, as well as the other levers examined in the SAFARI model, we developed a roadmap for an optimistic and sustainable decarbonisation trajectory for the transport sector in India. The CT scenario represents the status quo or baseline scenario. The Optimistic Decarbonisation (OD) scenario includes interventions such as fuel efficiency, electrification, ethanol blending (E10), and modal shifts, as shown in the roadmap in Figure ES4. We also assumed battery recycling, consumer preference for smaller personal vehicles, and technological improvements in battery chemistries and mineral intensities in this scenario to reduce the demand for critical minerals. Detailed milestones and policy directions to reach OD are shown in Table ES2.

Figure ES4: Roadmap for an Optimistic Decarbonisation (OD) trajectory

2030	2040	2050	2070
- Efficiency standards improvement over Current Trajectory (CT) by 5% - 1.7 times more annual EV sales than CT - Increase in rail share of intercity passenger transport by 2% over CT - 40 GWh battery recycling capacity - 10% CNG fuelled trucks - E10 blending mandate	- Efficiency standards improvement over CT by 8% - 90% more annual EV sales than CT - Increase in rail share of intercity passenger transport by 4% over CT - 90 GWh battery recycling capacity - 15% CNG fuelled trucks - E10 blending mandate	- Efficiency standards improvement over CT by 11% - 78% more annual EV sales than CT - Increase in rail share of intercity passenger transport and freight transport by 10% over CT - 120 GWh battery recycling capacity - 33% CNG, 5% electric and 5% H_2 fuelled trucks - E10 mandate and 15% biojet fuel share in aviation	- Efficiency standards improvement over CT by 11% - 15% less annual EV sales than CT due to increasing shift towards public transport - Increase in rail share of intercity passenger transport by 20% and freight transport by 25% over CT - 120 GWh recycling capacity - 70% CNG, 15% electric and 15% H_2 fuelled trucks - E10 mandate and 18% biojet fuel share in aviation

The OD scenario causes transport sector emissions to peak around 2040 and reach ~240 million tonnes of CO_2 ($MtCO_2$) in 2070 as shown in Figure ES5. The residual emissions are from the remaining 80% of the aviation sector and 70% of road freight that still relies on fossil fuels. The cumulative emissions (2020–2070) reduce from 40 gigatonnes of CO_2 ($GtCO_2$) in the CT scenario to 23 $GtCO_2$ in the OD scenario. Policies are already in place for almost all levers modelled in this study, and Table ES2 shows the enhancements in rate needed to transition to the modelled OD trajectory. In addition to the actions and target indicators listed in the table, we recommend continued investments towards enhancing the convenience and adoption of public transport in the long term.

Figure ES5: Annual emissions from India's transport sector moving from 'Current Trajectory' to 'Optimistic Decarbonisation'

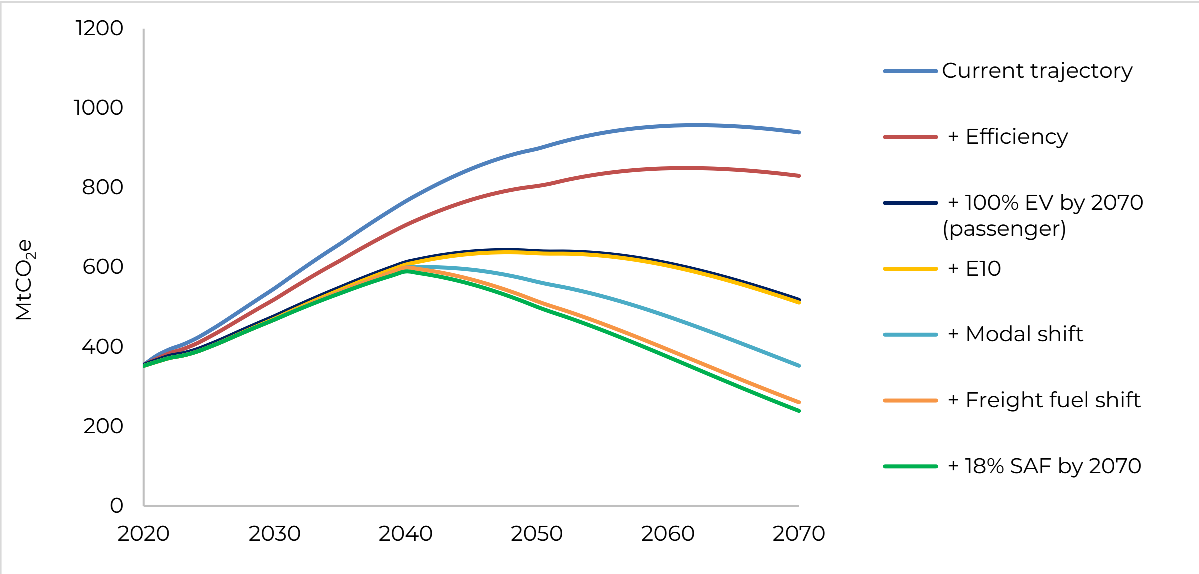


Table ES2: Policy directions to reach OD trajectory

Key stakeholder	Action	Target indicator	2030	2040	2050	2070
Ministry of Petroleum and Natural Gas (MoPNG)	Create a feedstock-production–linked dynamic ethanol mandate for blending with petrol in the short term and for bio-jet fuel production in the long term	Ethanol production for fuel use with minimal land use and groundwater trade-offs	10 billion litres (E10)	12 billion litres (E10 and 15% blending with jet fuel)	14 billion litres (E10 and 16% blending with jet fuel)	14 billion litres (18% blending with jet fuel)
Ministry of Railways and state governments	Measures to increase the intercity passenger transport share in the long term through continued investments in modernisation, high speed rail corridors, other capacity and service improvements, and leveraging multimodal connectivity opportunities	Share of railways in intercity passenger travel (% improvement over the current trajectory [CT])	20% (2%)	20% (4%)	25% (12%)	30% (20%)
	Continued infrastructure investments in increasing rail share of freight beyond 2050	Freight share of railways (% improvement over CT)	35%	35%	40% (5%)	60% (25%)
Ministry of Heavy Industries (MHI)	Continuing FAME scheme to enable more electrification of public transport and overall EV adoption with charging infrastructure	Boost in annual sales of electric passenger vehicles (2W, 3W, cars, and buses) compared to CT	1.7 x	90%	78%	-15%
Ministry of Finance	Continuing tax incentives (purchase and road) and low-interest loans for increased uptake of electric cars over ICE					
	Measures like reduced GST for EV battery and continued PLI schemes to help achieve price parity with ICE					
Ministry of Road Transport and Highways (MoRTH)	Purchase subsidy/incentives for scrapping/exchanging old ICE vehicles for EVs					

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Key stakeholder	Action	Target indicator	2030	2040	2050	2070
Bureau of Energy Efficiency (BEE) and Ministry of Road Transport and Highways (MoRTH)	Tighten emission standards and ensure compliance with complementary measures such as vehicular labelling	Overall emissions norms as a % improvement over CT	7%	18%	25%	40%
		Emissions norms for passenger cars in particular	68.5 gCO2/km (BEE proposed [2027–2032] norm is 91.7)	51 gCO2/km (BEE proposed [2032–37] norm is 70)	30 gCO2/km	0
Ministry of Heavy Industries	Enhanced production-linked incentives for recycling entities	EV battery recycling operational capacity	12 GWh	42 GWh	92 GWh	150 GWh
Ministry of Environment, Forest and Climate Change (MoEFCC)	Effective implementation of the Battery Waste Management Rules, 2022, to enhance recycling rate					
Ministry of Mines (MoM)	Recovery potential of recycling critical minerals from used batteries to be factored in the critical mineral policy					
Ministry of Housing and Urban Affairs (MoHUA)	Urban planning to enable more walking, cycling etc. and continued investments towards enhancing convenience and adoption of public transportation in the long term	Urban public transport (bus+metro+NMT) share (% improvement over CT)	55%	47%	53% (6%)	65% (28%)

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Abbreviations

ASI	Annual Survey of Industries
ASI	Avoid-shift-improve
BC	Battery Capacity
BCM	Billion cubic metres
BEE	Bureau of Energy Efficiency
CNG	Compressed natural gas
CO_2	Carbon dioxide
CSTEP	Center for Study of Science, Technology and Policy
CT	Current Trajectory
E10	10% Ethanol blending
E20	20% Ethanol blending
EMM	Electrolytic manganese metal
ET	Eco-shift Transition
EV	Electric vehicle
FAME	Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles in India
GDP	Gross Domestic Product
GHG	Greenhouse gas
$GTCO_2e$	Gigatonnes of CO_2 equivalent
HP	Horsepower
HPMSM	High-purity manganese sulphate monohydrate
ICEV	Internal combustion engine vehicle
IESS	India energy security scenarios
IFPRI	International Food Policy Research Institute
LT-LEDS	Long-Term Low Emission Development Strategy
Mha	Million hectares
MI	Mineral Intensity
MoEFCC	Ministry of Environment, Forest and Climate Change
MoM	Ministry of Mines
MoPNG	Ministry of Petroleum and Natural Gas
MoRTH	Ministry of Road Transport and Highways
$MtCO_2e$	Million tonnes of CO_2 equivalent
NTDPC	National Transport Development Policy Committee
OD	Optimistic Decarbonisation
pkm	Passenger-kilometre
PLI	Production-Linked Incentive
RE	Renewable energy
SAFARI	Sustainable Alternative Futures for India
SAM	Social Accounting Matrix
Tkm	Tonnes-kilometre
TR	Technology Reliance
TR*ET	Technology Reliance + Eco-shift Transition
TSAM	Transport-focussed Social Accounting Matrix

1. Introduction

Greenhouse gas (GHG) emissions from India's transport sector predominantly originate from road transport, which is responsible for 12% of the country's total energy-related carbon dioxide (CO_2) emissions (IEA, 2023b). Further, the transport sector affects quality of life in many ways (Byravan et al., 2017). For instance, it leads to air pollution, traffic congestion, noise pollution, and urban heat. To improve quality of life, it is thus necessary to decarbonise the sector and make it more sustainable. According to estimates by the International Energy Agency (IEA, 2023b), for India to achieve its net-zero target by 2070, emissions from road transport must peak in the 2030s and fall below current levels by 2050. To move to this trajectory, significant efforts are needed to promote strategic development, drive investments, promote coordination among several stakeholders, and effectively implement strategies. There is a substantial overlap between strategies to decarbonise and improve quality of life, and modelling techniques can help understand the impact of these strategies.

1.1. Contextualising the project

Globally and in India, several modelling exercises have been undertaken to examine the decarbonisation of the transport sector. The scenario narratives in these studies typically include a baseline or reference scenario and a set of alternative scenarios with distinct characteristics, tied to the avoid–shift–improve (ASI) framework introduced in the 1994 report by the German Parliament's Enquete Commission. Typical levers explored to reduce emissions include improvements in fuel efficiency, switching to alternative fuels such as biofuels, electrification of vehicles, and modal shifts to public transport (CSTEP et al., 2019; Dhar et al., 2017; Dhar & Shukla, 2015; ICCT, 2022; International Transport Forum, 2023b; Paladugula et al., 2018).

However, the transport sector is intricately tied to other sectors, and thus, decarbonisation strategies can have unintended consequences. For instance, biofuel blending in the United States led to increased corn prices, cultivation, fertiliser use, and land-use change emissions and an overall increase in CO_2 emissions (Chen et al., 2021; Lark et al., 2022). Similarly, lithium mining, which is central to the electric mobility transition, has several environmental impacts including potential groundwater depletion (Vera et al., 2023). Compact and dense cities that would reduce transport demand could instead increase energy demand from taller and more material-intensive buildings. To avoid such unintended trade-offs, it is crucial that the roadmap for transport sector decarbonisation dynamically accounts for inter-sectoral dependencies. While the aforementioned studies in India provide a good understanding of the impact of decarbonisation strategies on emission reduction and infrastructure requirements, the impacts on land, water, and critical minerals have not been explicitly estimated.

From an economics perspective, fuel and carbon taxes have been modelled to study transport sector decarbonisation. Studies have also investigated interventions such as pricing regimes (e.g. higher fuel taxes with allocated funds for mass transportation and facilities that encourage non-motorised transport). The ASI approach has been applied to limiting global warming to 2°C specific to India via carbon taxation to achieve decarbonisation in the transport sector (Emodi et al., 2022; Mittal et al., 2015). Other measures explored include promoting higher vehicle occupancy, a higher share of non-motorised transport, increased adoption of zero-emission vehicles, and substantial investments in mass transit systems. However, the macroeconomic impacts of these decarbonisation strategies have not been fully explored, mainly because the social accounting matrix (SAM) that forms the basis for many of the economic models is not disaggregated to include sectors such as electric vehicles (EVs) or biofuels.

To complement this rich collection of literature, this study aims to fill three main research gaps focusing on biofuels and EVs:

- What is the additional land and water requirement to meet India's biofuel policy, considering the competing demands for maintaining food and nutritional security?
- What is the demand for critical minerals from the transport sector in India under a 'net zero by 2070' scenario?
- What is the macroeconomic impact of biofuel use (ethanol blending) versus that of transport electrification in India?

1.2. Project objectives

This study aimed to examine various decarbonisation options in the transport sector while considering its interconnectedness with the rest of the economy. The specific objectives of this study are as follows:

1) To evaluate the environmental and natural resource implications of ethanol blending in India
2) To estimate the demand for critical minerals (used in batteries) under different electrification scenarios
3) To analyse the macroeconomic implications of ethanol blending and electrification, including aspects such as job creation, sectoral growth, and income inequality
4) To develop a roadmap for the sustainable decarbonisation of the transport sector with minimal cross-sectoral trade-offs

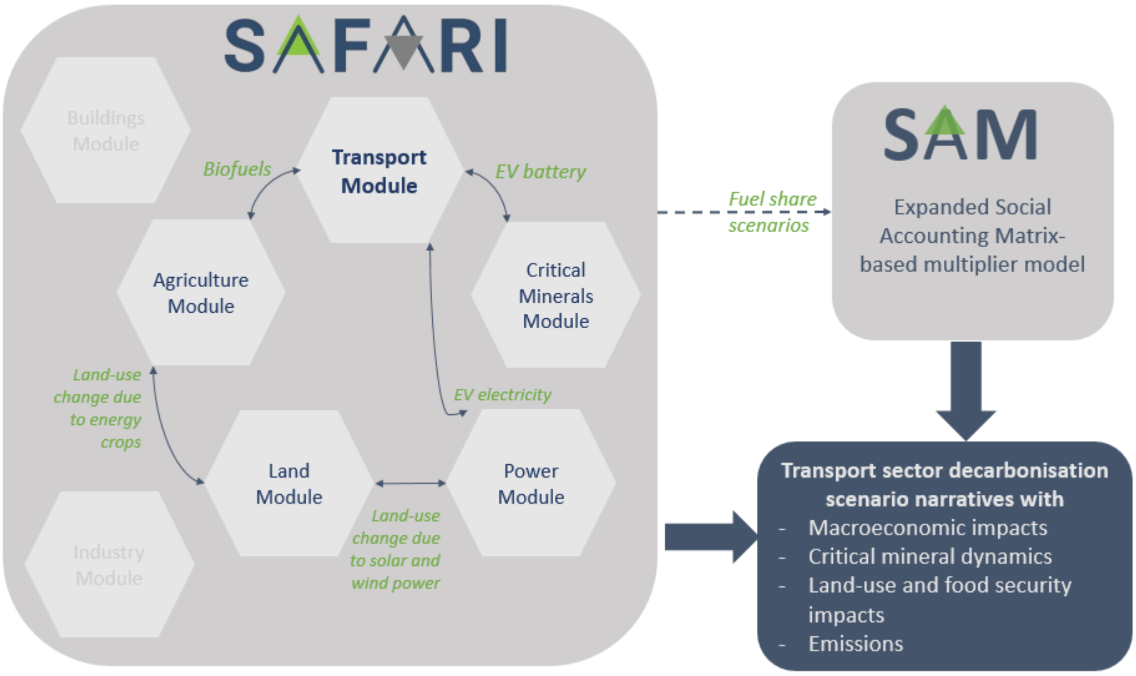
In terms of policy implications, the findings of this study can be mapped to the key climate and transport-related policies pursued by the Government of India. India's Long-Term Low Emission Development Strategy (LT-LEDS) document emphasises developing an 'integrated, efficient, inclusive, low-carbon transport system'. It mentions biofuels and electrification as key interventions for achieving this objective. This study highlights quantitative insights, contributing to the discourse on the LT-LEDS formulation process for India's transport sector. The study outputs are also relevant to any long-term biofuel policy building on the National Biofuel Policy to optimise targets considering net system costs–benefits, food security, and resource security. The Ministry of Mines has identified critical minerals specific for India, considering supply risk and economic importance. This study adds to this understanding by bringing in the demand aspect using a bottom-up modelling framework, expanding the understanding of supply–demand dynamics of critical minerals and import dependency and thereby the overall feasibility of the transition to a clean transport system. The LT-LEDS briefly mentions that India will consider policies related to the management of EV-related waste and circular economy principles for the EV sector. Further, the draft National Resource Efficiency Policy (2019) references the need for incentivising material substitution and use of recycled materials in EV fleets. The study's findings can potentially contribute to concretising the targets for such policies.

2. Methodology

2.1. Modelling approach and frameworks

Two modelling frameworks have been used for this study: the Sustainable Alternative Futures for India (SAFARI) model and SAM-based multiplier. The study approach is presented in Figure 1.

Figure 1: Schematic of the modelling approach



2.1.1. SAFARI model: Environment, materials, and natural resources

SAFARI is a system dynamics simulation model that incorporates all major sectors of the economy and their interlinkages, assessing energy, emissions, and resource implications of achieving various developmental goals until 2100 (Ashok et al., 2021; CSTEP, 2021; P. Kumar et al., 2021). The model allows the exploration of implications and trade-offs among sectors, enabling sectoral deep-dive studies and country-wide modelling studies considering sectoral interlinkages.

The SAFARI model includes a detailed representation of transport modes and fuels, allowing the impact analysis of mitigation options. It estimates emissions from different modes and fuels, identifies potential emission reduction opportunities, and assesses interventions such as modal shifts in passenger and freight transport. The model also considers critical raw materials and their supply–demand dynamics, recyclability, and replaceability, bringing a circular economy perspective to the analysis of transport decarbonisation options. The SAFARI model's agriculture and land-use module enables the analysis of the implications of fuel shifts to ethanol in the transport sector, considering different feedstock varieties and their impacts on arable land and freshwater resources. The environmental impact, including emissions and the adoption of efficient irrigation practices and hybrid crop varieties in future scenarios, can also be examined. Further, the impact of transport electrification on the power sector can be explored in detail using the SAFARI framework.

2.1.2. SAM model: Macroeconomic implications

SAM represents economic transactions among all agents in the economy for a specific period, which is useful for estimating macroeconomic indicators such as gross domestic product (GDP), gross value added, labour and capital intensity, and household income. SAMs and SAM-based multiplier models have been widely used to analyse the economic impacts of various sectors. The history of SAM models in India is provided in Appendix A.

To understand the macroeconomic implications of fuel shifts, the existing SAM model with a 2017–18 base year was expanded to segregate transport by mode and fuel type. This enabled a detailed analysis of electrification scenarios and provided insights into the economy-wide impacts of modal shifts in passenger transport. The resulting multiplier model was linked to the SAFARI model to build scenarios to analyse cost and distributional impacts, changes in GDP, household income, expenditure, and employment across rural and urban areas. This could provide valuable insights into established decarbonisation measures such as EV adoption and ethanol blending.

In this study, we employed data from the 2017–18 Periodic Labour Force Survey to assess the employment impacts of each scenario in terms of the actual number of jobs created.

2.2. Model set-up and assumptions

This section includes the technical details of the relevant modules of the SAFARI and SAM-based multiplier models.

2.2.1. SAFARI transport module

Historical trends in passenger-kilometre (pkm) per capita were analysed to derive a growth rate for India. The pkm per capita has historically risen with increasing incomes but tends to plateau at a certain income level in developed countries. This plateau occurs because despite higher incomes, people are generally unwilling to spend more than about 1.1 hours per day on commute. The saturation level of pkm/capita varies by country and is influenced by factors such as demographics, infrastructure investments, and urban design and density. For example, Japan's pkm/capita saturated at 10,000 km, whereas it reached 27,000 km in the United States. For India, based on the ranges provided in literature and discussions with experts, a saturation level of 18,000 km was assumed in the model, producing an S-shaped trajectory. The total passenger transport demand was then determined as follows:

$$Total\ pkm = \frac{pkm}{capita} \times total\ population$$

Further, to distribute the total pkm between urban and non-urban areas, Indian cities were categorised as ‘urban 1’ (population > 5 million) and ‘urban 2’ (population < 5 million). Relevant data for urban pkm (including the number of trips per day per person and trip length per trip) have been collated by the United Nations Environment Programme from various sources, such as the Planning Commission’s study on traffic flows, the Ministry of Urban Development’s study with the Wilbur Smith Association (WSA) on urban transport, and other studies in Indian cities. The urban pkm was thus calculated as follows:

$$Annual\ urban\ pkm = \frac{trips}{day} \times \frac{trip\ length}{trip} \times population \times 365$$

The non-urban pkm was then derived as shown below:

$$Annual\ nonurban\ pkm = total\ pkm - annual\ urban\ pkm$$

Overall, 2% of the non-urban pkm was assumed as rural, with non-motorised transport and two-wheelers (2Ws) being the primary transport modes. The remaining modes included intercity travel via air, rail, and road (bus or car). Urban transport modes considered included public (bus, metro, and suburban rail), private (cars, 2Ws, and three-wheelers [3Ws]), and non-motorised modes, based on current trends and literature from the India Energy Security Scenarios (IESS) and National Transport Development Policy Committee (NTDPC). The fuels for the passenger transport module included petrol, diesel, electricity, compressed natural gas (CNG), ethanol, biodiesel, and bio-jet fuel.

Similarly, for freight transport, historical growth rates for tonnes-kilometre (tkm) per capita were used to project future demand without distinguishing between urban and intercity freight. Data sources include NTDPC, Indian Railways Yearbook, Directorate General of Civil Aviation, IESS, and Organisation for Economic Co-operation and Development statistics. Freight modes were distributed among road, rail, air, and water. Fuel efficiency assumptions incorporated standards for heavy vehicles from the Ministry of Power, Bureau of Energy Efficiency, Lawrence Berkeley National Laboratory, and International Council on Clean Transportation.

The transport module interacts with the agriculture module via ethanol demand/supply, with the power module via electricity demand from EVs, and with the critical minerals module via battery requirement for EVs, as shown in Figure 2.

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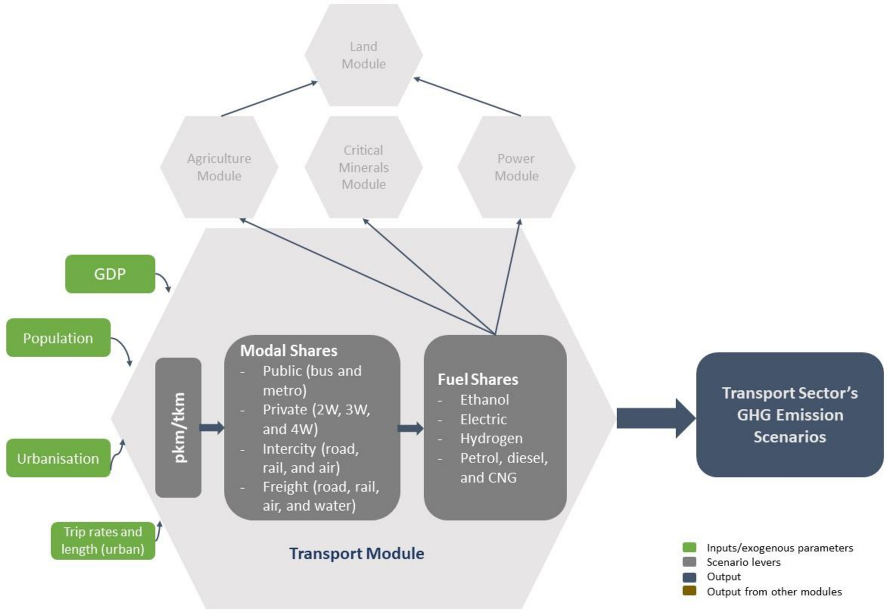
Figure 2: Schematic of the SAFARI transport module



For urban areas, the resultant vehicular emissions (particulate matter, volatile organic compounds, nitrogen oxides, and carbon monoxide) and national-level transport sector GHG emissions (CO_2, nitrous oxide, and methane) were estimated based on modal shares, fuel shares, fuel efficiency, and emission factors.

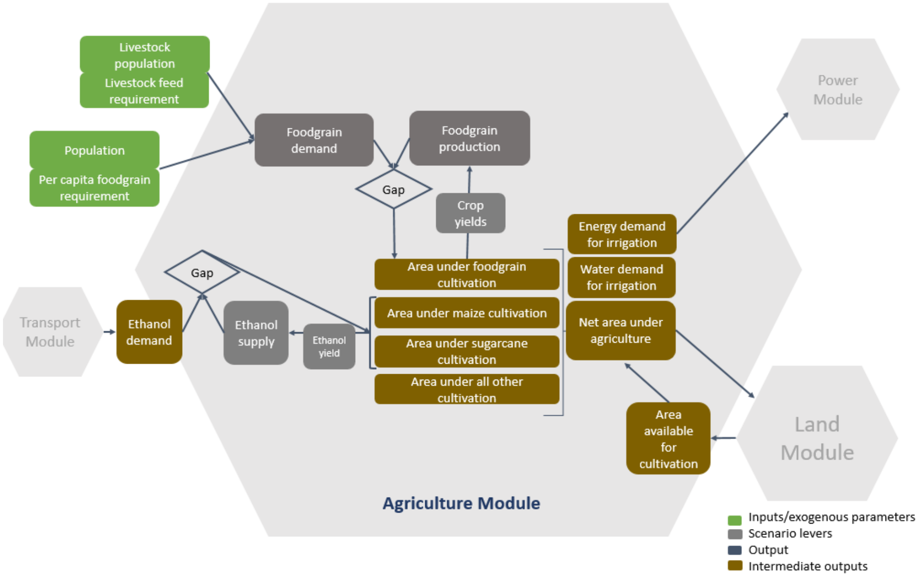
2.2.1.1. Key scenario levers

- Modal shares:
    - Urban transport: % share among 2Ws, 3Ws, cars, cabs, buses, metro, and non-motorised transport
    - Intercity passenger transport: % share among road, rail, and air
    - Freight transport: % share among road, rail, water, and air
- Fuel shares
    - Urban passenger transport: for each vehicle type (2Ws, 3Ws, four-wheelers [4Ws] including cars and cabs, and buses), % share among petrol, diesel, electric, and CNG
    - Freight transport: % share among diesel, electricity, CNG, and hydrogen
- Ethanol blending mandate
    - % blending and target year (this informs the ethanol demand, which is connected to the agriculture module)

2.2.2. SAFARI agriculture module

The SAFARI agriculture module is fundamentally a goal-seeking module wherein the crop production must meet multiple goals of food security (for direct food consumption and indirect consumption via livestock feed requirement) and ethanol demand from the transport module. Figure 3 provides the schematic of the module.

Figure 3: Schematic of the SAFARI agriculture module



The model is initiated with the actual area under cropping for foodgrains (rice, wheat, maize, nutri-cereals, and pulses) and other crops (sugarcane and all other crops). It also provides information on crop yields, which is a function of the share of each crop area under irrigation vs rainfed crop area. The overall yield was calculated as follows:

$$Overall\ yield_i = (Rainfed\ yield_i \times Rainfed\ area_i) + (Irrigated\ yield_i \times Irrigated\ area_i),$$

where *i* represents each type of crop. In SAFARI, the yield is dependent on the area under irrigation, type of irrigation, and use of high-yielding crop varieties.

The model then runs dynamically and checks if there is sufficient crop production to meet the requirement of foodgrains for direct consumption, livestock feed, and ethanol demand. If a production–demand gap is computed by the model for any crop, the corresponding crop area is increased in proportion to the gap.

The net area under cropping interacts with the land module of the SAFARI model. The land module captures the dynamic interaction among different land-use types—net sown area, fallow land, built-up area, land for growing solar and wind power, and forests. This module thus informs the availability of arable land for agricultural expansion under various scenarios, which sensibly constrains the cultivation area.

Water is crucial for agriculture, the largest water withdrawer among all sectors[1]. The total water withdrawal for irrigation was calculated based on crop water requirement, irrigation type, and corresponding efficiency.

$$Number\ of\ pumps = \frac{Groundwater\ demand}{Average\ discharge\ rate\ \times Functioning\ hours\ per\ year}$$

$$Average\ discharge\ rate\ (gpm) = \frac{Pump\ HP\ \times Efficiency\ \times 3960}{Dynamic\ head\ (ft)}$$

Because of regional variations in variables such as pump capacity (horsepower [HP]) and dynamic head, we assumed a weighted average based on data from the Minor Irrigation Census. Based on the fuel share, average HP, and total number of pumps, the pumping energy requirement in terms of electricity, solar, and diesel was estimated. The electricity demand interacts with the SAFARI power module.

For the context of this study, this module was appropriate for estimating food security, land, water, and energy consequences under various ethanol blending ratio and feedstock scenarios.

2.2.2.1. Key scenario levers

- Share of ethanol from maize and sugarcane as feedstock
- Sugarcane feedstock share for ethanol: B-molasses, C-molasses, and sugarcane juice
- Fraction of area under cropping under precise irrigation
- Lever to regulate area under sugarcane cultivation (as a water-saving strategy)
- Fraction of area under irrigation via surface water vs groundwater
- Irrigation: conveyance and application efficiency targets
- Cropping intensity

2.2.3. SAFARI critical minerals module

As described earlier, the transport module in SAFARI includes all parts of the transport sector in India and is driven by population growth and GDP. Based on assumptions described previously, SAFARI projects travel demand in terms of the pkm for each mode and fuel type. For this study, we considered road-based passenger transport, which includes 2Ws, 3Ws, 4Ws, and buses. The number of EVs in each of these modes was back-calculated from the projected pkm using the given formula:

$$Number\ of\ vehicles\ = pkm\ /\ (average\ annual\ distance\ *\ average\ occupancy)$$

[1] The model structure has the option for the annual water availability (1,123 bcm/year) to act as a constraint and critically impact food security, but it is disabled in the business-as-usual scenario to reflect the current practice of over-extraction of groundwater using pumping power.

As shown in the flowchart (Figure 4), we calculated the mineral demand based on our assumptions (Table 1) of battery capacity, share of lithium-ion, battery chemistries, and mineral intensity.

Figure 4: Schematic of the SAFARI critical minerals module

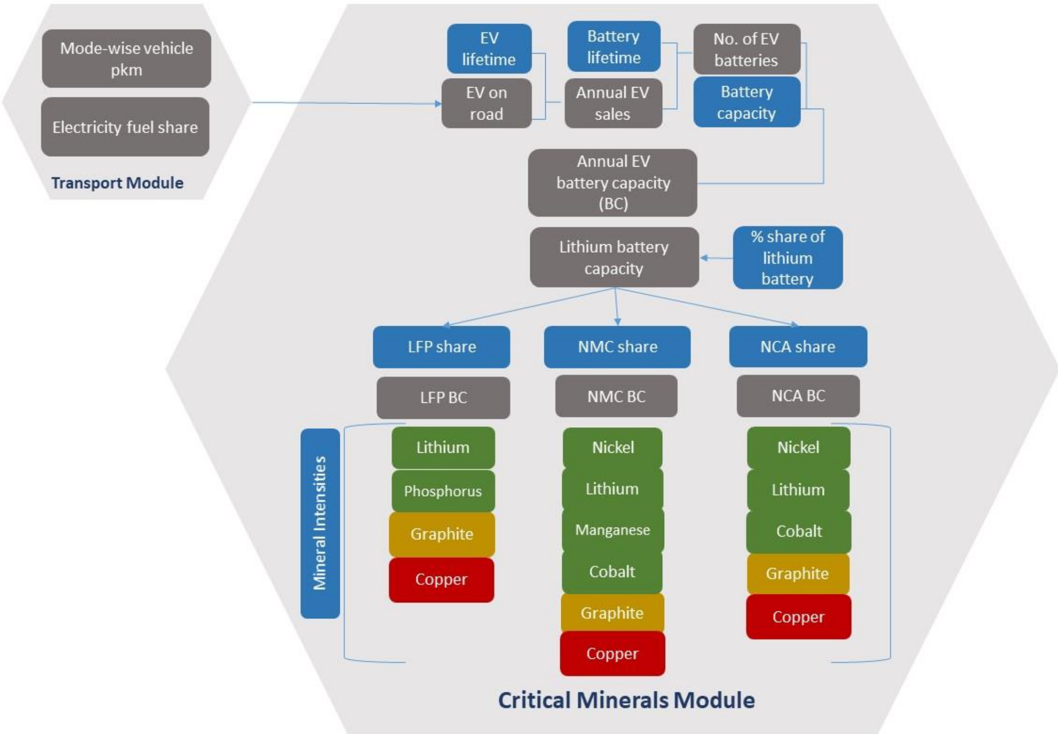


Table 1: Transport sector assumptions related to EVs for the year 2024

	Average annual distance (km)	Average occupancy	Average vehicle lifetime (years)	Average battery life (years)	Average battery capacity (kWh)
Two-wheeler	6,500	1.5	10	5	4.3
Three-wheeler	35,000	1.76	8	4	6
Four-wheeler	30000	3	13.5	7	30
Buses	90,703	41.6	10	6	170

Sources: (International Council on Clean Transportation, 2021; International Transport Forum, 2023a)

In the Current Trajectory scenario, we assumed vehicle and battery life to increase slightly over time because of technological advancements. We also assumed battery capacity per vehicle to increase over time to 7.5, 10, 80, and 350 KWh for 2Ws, 3Ws, 4Ws, and buses, respectively, by 2070 to meet the demand for bigger vehicles and better range (International Council on Clean Transportation, 2021). The lithium-ion battery capacity share of the total EV battery capacity was assumed to be 76% in 2024 (Gautam, 2022), increasing to 90% in 2070. The battery chemistry share was assumed to be 30% for lithium iron phosphorus (LFP), 60% for nickel manganese cobalt (NMC), and 10% for nickel cobalt aluminium (NCA) for 2024 (IEA, 2023a); this share was 40% for LFP and 60% for NMC in 2070.

2.2.3.1. Key scenario levers

- Battery capacity
- Battery lifetime
- Mineral intensity
- Battery chemistry
- Recycling rate

2.2.4. Transport-focussed SAM (TSAM)

SAMs form the basis of many kinds of macroeconomic models. A SAM is a representation of all economic transactions taking place within a country for a given year (base year). All major economic agents such as industries, governments, and households are depicted in SAM. Unlike input–output tables, SAM considers the entire circular flow of income in the economy by accounting for household earnings from various sources and expenditures. As a result, it can be used for macroeconomic modelling studies that aim to assess the impact of exogenous shocks on the economy, accounting for the linkages among sectors and agents. The two most widely used models based on SAM are multiplier and computable general equilibrium models.

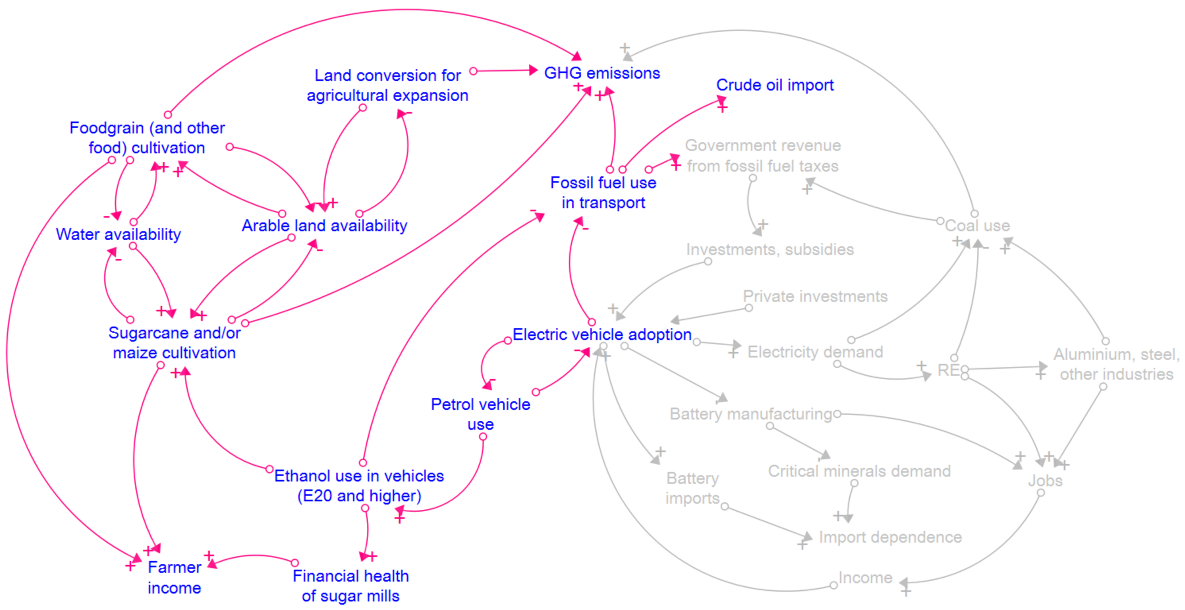
The first SAM for India was constructed by Sarkar and Subbarao (1981). However, SAMs must be constantly updated over time to utilise the better data available, reflect the changing structure of the economy, include newer sectors that have emerged, emphasise the representation of certain sectors, and so on. As a consequence, various SAMs have been constructed for India over time. Table A1 in Annexure presents an overview of SAMs that have been constructed and published for India over time. India is expected to experience significant changes in its economic structure in the near future, driven by increasing per capita income that results in higher energy consumption and associated emissions. Furthermore, with climate issues gaining prominence in the policy discourse, a transition to cleaner fuels and technologies is expected.

Previously, the Center for Study of Science, Technology and Policy (CSTEP) worked on disaggregating the representation of the power generation sector using a SAM model with the base year 2017–18 to distinguish between electricity generated from renewable (solar, hydro, wind, and biomass) and non-renewable (such as coal and gas) sources. To do this, we started with the nexus SAM published by the International Food Policy Research Institute (IFPRI) (Pal et al., 2020). This SAM compiled data from various government data sources such as the National Sample

Survey 68th Round, National Accounts Statistics, Supply-Use Table 2015–16, and UN Comtrade database 2017. However, this SAM was primarily constructed for analysis of food and agricultural policies, making it less relevant for energy and transport policy analysis. To ensure better representation of energy-related sectors, CSTEP utilised the 2017–18 Annual Survey of Industries (ASI) dataset (Central Statistics Office, 2020). ASI is a comprehensive, nationwide sample survey conducted annually to gather detailed information on various sectors, specifically manufacturing, repair services, gas and water supply, and cold storage. It aims to collect data on a wide range of metrics, including assets and liabilities, employment and labour costs, receipts and expenses, and indigenous and imported input items. Additionally, ASI captures information on products and by-products manufactured, taxes, and distributive expenses. By doing so, it provides valuable insights into the financial health and capital structure of industries, labour dynamics and costs, income and expenditure patterns, supply chain dependencies, production trends, and tax compliance. These data are crucial for policymakers, economists, and businesses, as it offers an in-depth view of the industrial sector's performance, structure, and contributions to the economy. CSTEP mapped the ASI sectors to the IFPRI SAM sectors using the National Industrial Classification (Central Statistical Organisation, 2008) and National Product Classification (Central Statistics Office, 2011) codes and disaggregated the intermediate input use, factor use, and taxes paid by energy-related sectors, most importantly power generation. This helped gain a thorough understanding of the impacts of renewable energy (RE) policies (such as a higher percentage of renewables in the grid, taxing fossil-fuel energy, and subsidising RE) on labour and capital employed, household income and expenditure, and overall economic growth.

To facilitate a deeper analysis of the impacts of transport decarbonisation policies, such as passenger transport electrification and use of ethanol-blended fuel, we further disaggregated the transport sector by mode and fuel type. For this, we used data on electric and non-electric vehicle ownership by households from the Ministry of Road Transport and Highways' VAHAN database (MoRTH, 2023). We also structured SAM such that ethanol was used by the petroleum-refining sector to produce ethanol-blended fuel. With this TSAM, a multiplier model was built to perform scenario analysis for studying the spillover macroeconomic impacts of key supply- and demand-side transport decarbonisation measures.

3. Biofuels: Land, Water, and Food Security Implications



Rising ethanol demands to maintain E20, whether met by maize or sugarcane or a combination of both, will require additional land. This will lead to the quicker uptake of fallow land and increased conversion of forest land into agricultural land. The use of sugarcane will also lead to excessive water withdrawals, particularly in India's drought-prone regions. Maintaining the E10 blend, instead, presents fewer compromises while preserving the advantages of ethanol blending. E10 can be sustained through existing sugarcane cultivation for sugar production and is compatible with current vehicles without requiring changes to infrastructure or design. E10 is the best way forward unless there is a breakthrough on cellulosic or algal biofuels.

In India and across the world, policies to promote ethanol blending with petrol have been implemented. These policies typically have multiple benefits, including improvement in air quality, in addition to achieving energy security and emission reduction. However, as discussed in Section 1, recent studies in the United States have shown that ethanol production and blending can have more trade-offs than benefits depending on the feedstock and technology. Lark et al. (2022) found that the implementation of the Renewable Fuel Standard (which is the ethanol blending programme in the United States) led to an increase in the prices of corn and other crops, which in turn led to increased cultivation, fertiliser use, and emissions from land-use change and an overall increase in the carbon intensity of corn-based ethanol production. Another study (Chen et al., 2021) also supported this finding and concluded that the ethanol blending mandate resulted in increased net costs in the country (both economic and environmental) compared with a hypothetical counterfactual scenario. Studies also explored the impact of first-generation biofuels on food security and ways to minimise these negative effects (Naylor et al., 2007; Tilman et al., 2009).

In India, the majority of ethanol produced uses sugarcane as a feedstock. The Government of India has set a target to achieve a 20% blending rate of ethanol (E20) with petrol by 2025 (NITI Aayog, 2021b). In addition to reducing emissions, the motivation for this policy includes reducing import dependency for crude oil, improving farmer income and air quality, and dealing with surplus sugar production. In 2021, the World Trade Organization (2021) stated that subsidies provided for sugar production in India were inconsistent with global trade rules and resulted in a sugar surplus, which was detrimental to the global sugar trade. India was then banned from exporting sugar, resulting in a surplus in the country. As the surplus sugar could not be exported, it was ascertained that it could instead be diverted for ethanol production.

Sugarcane is a water-intensive crop and is grown in some of India's drought-prone regions (West Zone Water Partnership, 2016). National- and regional-level analyses using the SAFARI model (Ashok et al., 2021) show that growing too much sugarcane exacerbates groundwater issues, which would then impact food security. To address these issues and augment sugarcane-based ethanol, the government launched a scheme, the Pradhan Mantri JI-VAN Yojana scheme, which provides financial support to integrated biofuel plants, particularly those using lignocellulosic feedstock (or second-generation [2G] ethanol). Because 2G ethanol production uses biomass waste and crop residues, it would limit the impact on food security and lead to reduced emissions and improved air quality because of reduced biomass burning. While there are co-benefits to producing 2G ethanol, it has not had much success globally, with most plants being shut down. Hence, the future of 2G ethanol production in India depends on further research and development in addressing barriers to its scalability and productivity. Another measure taken by the government to reduce dependence on sugarcane for ethanol production is to incentivise the use of maize, which has a lower water footprint, as a feedstock for ethanol production. Maize is predominantly used as a feed for poultry and livestock in India, accounting for nearly 63% of the production (Indian Council of Agricultural Research, 2011). It is also a staple food for certain parts of the country. Nearly 87% of the maize produced is directly or indirectly used as food. Further, while the amount of water required per tonne of maize cultivated is less than that required per tonne of sugarcane, the overall water required to produce ethanol from both sources is similar because of the significantly lower yield of maize (Gerbens-Leenes et al., 2009).

It is imperative to understand the possible trade-offs of sustaining an ethanol blending mandate in India by evaluating its implications on land-use and water and food security. In this section, these aspects have been delineated using a nexus-based approach with the SAFARI model.

3.1. Scenarios

The literature on demand projections of food in India is predominantly based on demand-elasticity studies, which rely on household survey data on consumption patterns. The indirect demand for foodgrains, which includes seed, feed, wastage, and other uses, is conventionally estimated as a fraction of the foodgrain production. We ran most scenarios under this feed assumption, wherein we calibrated the livestock feed demand for foodgrains to the latest official estimates (NITI Aayog, 2024).

However, as mentioned before, maize is a critical crop for livestock feed, particularly poultry feed. To further understand the potential implications on food and nutrition security, we ran some 'Feed Prioritisation' scenarios wherein the feed was estimated based on the livestock population in a bottom-up manner (rather than as a fraction of the foodgrain production). In the model, the livestock population was assumed to grow to achieve the nutrition norms set by the Indian Council of Medical Research (180 eggs per capita per year, 10.8 kg poultry meat per capita per year, and 300 g milk per capita per day by 2050)[2]. Based on this population, the average foodgrain requirement for livestock feed was estimated in a bottom-up manner. The scenarios simulated are described below:

1) No Policy: This is a hypothetical scenario wherein the National Policy on Biofuels 2018 is not implemented, resulting in a 0% blending rate until 2070. Sugarcane cultivation is expected to continue with historical trends without responding to ethanol or sugar demands (leading to a consistent sugar surplus).
2) E20 via 50–50 Maize–Sugarcane (E20 50–50): E20 blending is achieved and sustained, with ethanol supply evenly met by maize and sugarcane, following the policy roadmap (NITI Aayog, 2021b). In this scenario, the yield of maize is assumed to increase linearly from 3.5 tonnes per hectare today (as per the Indian Institute for Maize Research) to 5 tonnes per hectare by 2070. Sugarcane yield is assumed to increase from 80 tonnes per hectare (as per Indian Institute for Sugarcane Research) to 100 tonnes per hectare by 2070 across all scenarios.

[2] There is a huge gap between the norms and present day average consumption of high-value food commodities, such as egg, meat, and milk, which is why the target year was set to 2050.

a) **E20 50–50 with High-Yield Maize (E20 50–50 HYM):** This is similar to the previous scenario but with maize yields increasing to 8.5 tonnes per hectare by 2070.

b) **E20 50–50 with Feed Prioritisation (E20 50–50 FP):** Instead of the assumed feed demand, the feed demand calculated bottom-up to meet the nutrition norms (as described previously) is considered.

c) **E20 50–50 FP+HYM:** This is a combination of the two previous sub-scenarios.

3) **E20 via Sugarcane Alone (E20 100 SC):** A scenario wherein all ethanol demand for E20 is met exclusively by sugarcane.

4) **E10 Continuation:** A scenario where the E10 blending rate remains constant at current levels until 2070, with no increase in the blending rate.

3.2. Results and discussion

The SAFARI transport module projects a rising petrol demand, despite the expected increase in EV uptake. This implies that maintaining the E20 target leads to an **increase in demand for fuel ethanol**: 10 billion litres by 2025, 12 billion litres by 2030, and 20 billion litres by 2050. The rising demand necessitates a significant increase in land.

- Across scenarios, we found an increase in maize cultivation (Figure 5) up to around 2050, beyond which there is a slight decline because of a combination of various factors such as reduced population growth, yield improvements, and increased EV uptake (reducing ethanol demand).
- Compared with the No Policy scenario, in the E20 50–50 scenario, wherein ethanol demand is equally met by sugarcane and maize, approximately 8 million hectares (Mha) of additional land will need to be allocated for maize cultivation by 2030 and up to 10 Mha by 2050. The current area under sugarcane cultivation (less than 5 Mha) is sufficient to meet the remaining demand.
    - If maize yields drastically improve to 8.5 tonnes per hectare by 2070 (E20 50–50 HYM), the additional land requirement drops to about 5.7 Mha by 2030 and reduces thereafter, as illustrated in Figure 5.
    - With the bottom-up feed estimation, the baseline demand for maize itself increases. Further, when maize for ethanol is also included, the gross area under cultivation for maize will be significant at ~35 Mha by 2050 (E20 50–50 FP).
- In the E20 100 SC scenario, wherein all ethanol demand is fulfilled by sugarcane, around 3.5 Mha of additional land will be required for sugarcane cultivation over the next few decades (Figure 6). There will be no need for increased maize cultivation.

Figure 5: Area under maize cultivation

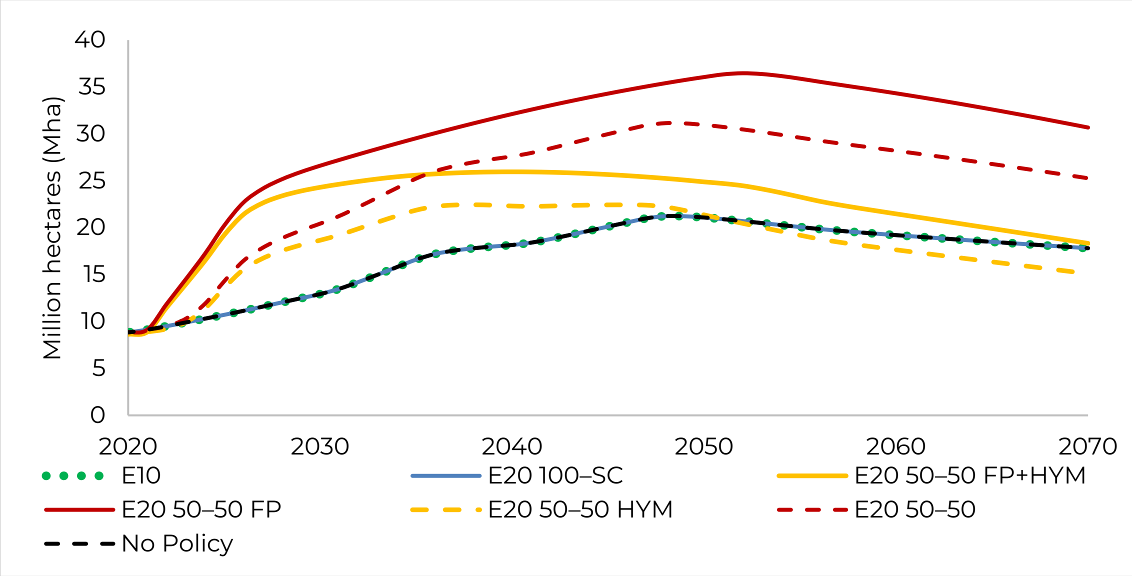
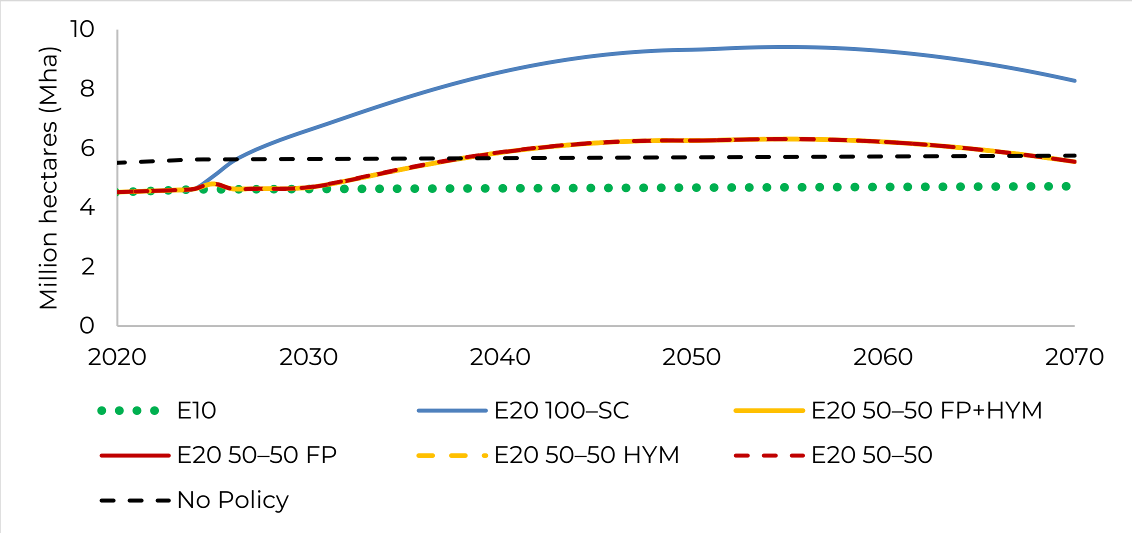
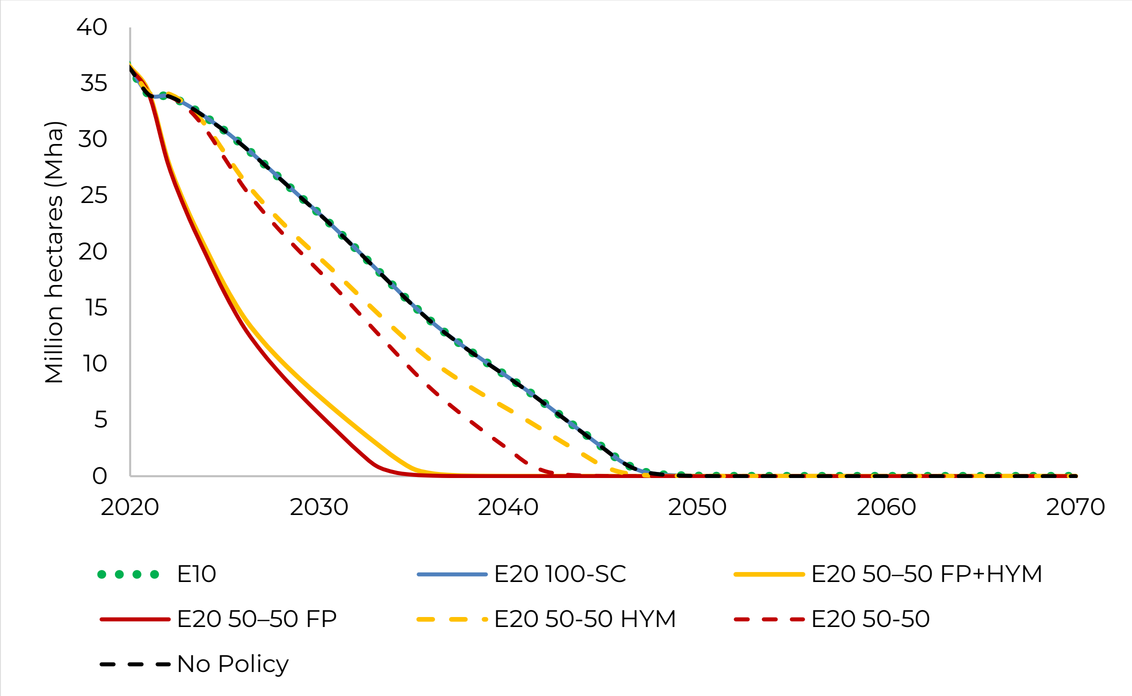


Figure 6: Area under sugarcane cultivation



Increased land footprint of E20, particularly in scenarios wherein maize is used as a feedstock for ethanol, results in fallow land running out by around 2040 (Figure 7). In the scenario prioritising livestock feed demand, fallow land runs out 8–10 years earlier. These factors indicate the trends of increasing demand pressures for maize supply and possibility of food price inflation, ultimately impacting food security. Consequently, this will increase the pressure on land resources and other land-use types, particularly putting the forest land at risk for conversion, and by extension, compromising the net carbon sink. In contrast, this directs towards the need for significant changes in cropping patterns and practices to increase the yield and cropping intensity and reduce the net land requirement for cultivation.

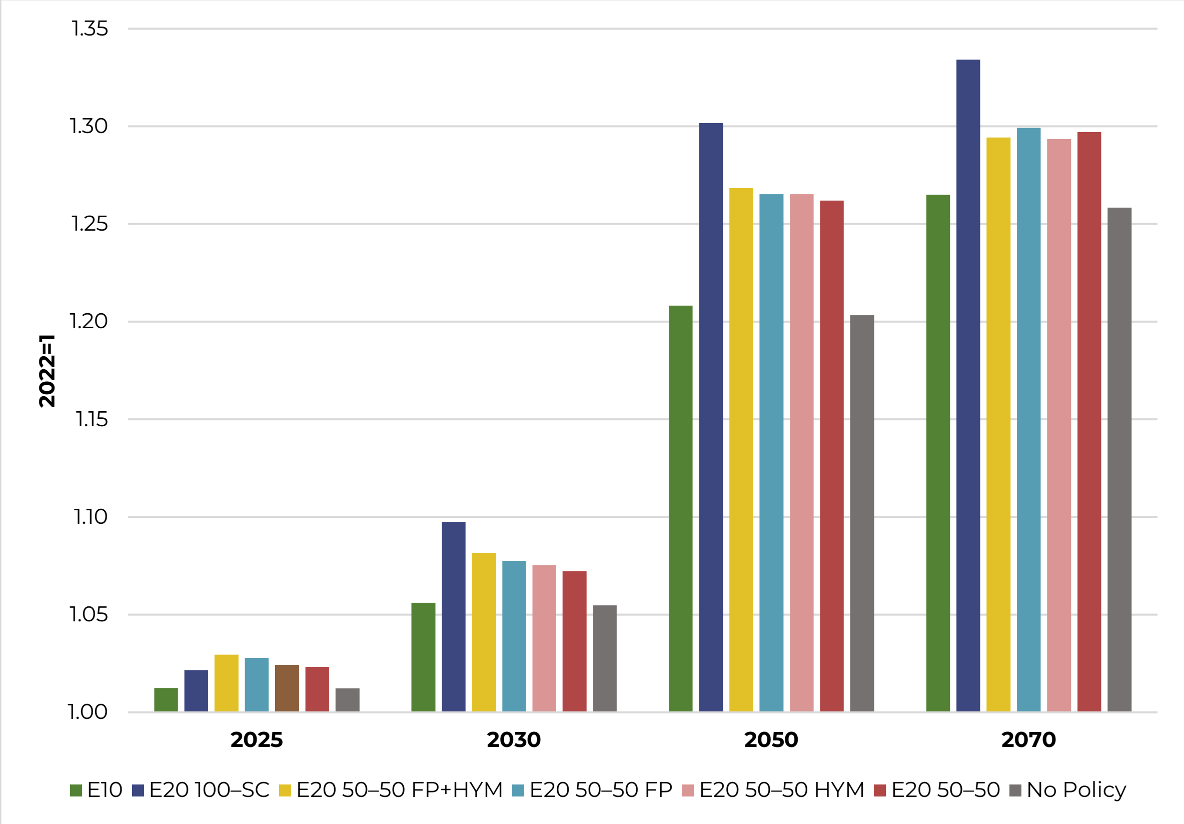
Figure 7: Fallow land (net remaining arable land available for cultivation)



Sustaining an E20 blending rate significantly increases the water footprint compared with the No Policy or E10 scenario:

- In the E20 50–50 scenario, wherein ethanol demand is split between maize and sugarcane, the annual average irrigation water demand is projected to rise by approximately 30–50 billion cubic metres (BCM) by 2070 (Figure 8).
- In the E20 100 SC scenario, wherein all ethanol demand is met by sugarcane, the total annual irrigation water demand can increase by up to 60 BCM.
- The E20 50–50 HYM scenario results in a comparatively lower land and water footprint. However, with substantial yield increases, India must decide whether to allocate more maize for ethanol production or to address the often-underestimated demand for livestock feed.

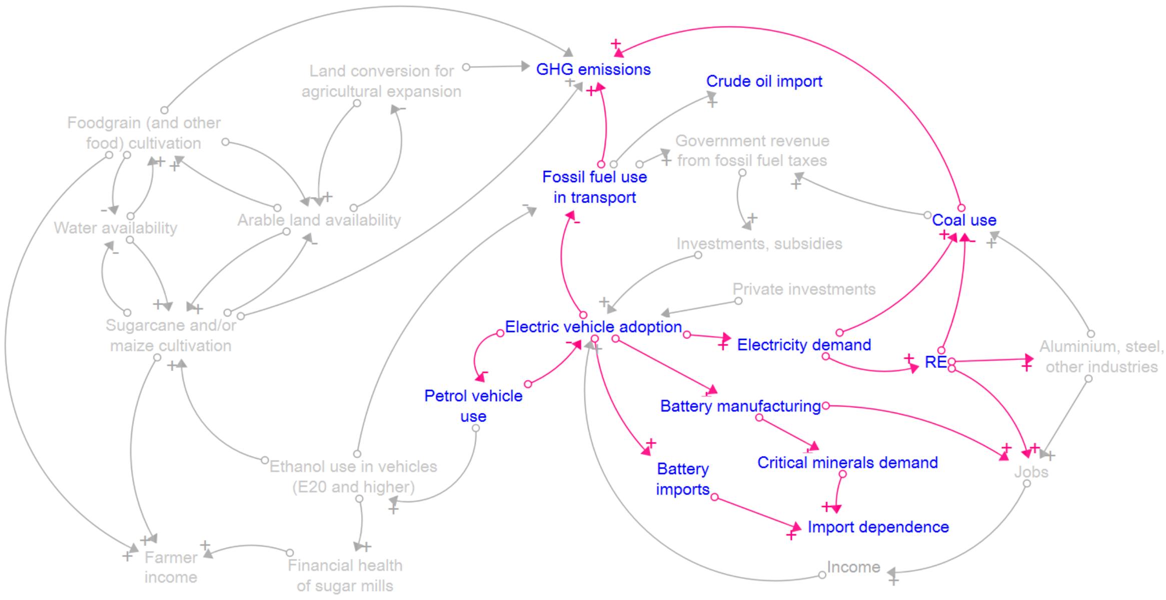
Figure 8: Increase in agriculture water demand compared with 2022 levels



E10 is a more sustainable pathway with the least trade-offs. Ethanol demand to maintain E10 (6 billion litres by 2030, 9.5 billion litres by 2050, and 8.3 billion litres by 2070) can be met with the current sugarcane cultivation levels. This will involve using varying proportions of B- and C-molasses and sugarcane juice, without requiring maize. Consequently, this approach avoids the food (and feed) versus fuel dilemma. Additionally, existing vehicles can handle E10, eliminating the need to upgrade fuel tanks and engines.

To summarise, until and unless cellulosic ethanol (2G) or other breakthrough technologies to produce ethanol sustainably become viable, maintaining the E10 blend may be the best strategy for India's ethanol blending programme.

4. Transition to EVs: Demand for Critical Minerals



The electrification of transport will increase India's demand for critical minerals including graphite, nickel, copper, and lithium, impacting energy security due to import dependency. To reduce mineral demand while pursuing net zero, strategies such as battery recycling, uptake of smaller vehicles, and shifting away from lithium-ion batteries are essential. A shift to LFP batteries, however, increases demand for phosphorus, critical for agriculture. Combining these strategies with the promotion of public transport can significantly lower India's mineral needs by 2070.

The growth in the EV sector and the number of EVs have a cascading effect on the demand for batteries and critical minerals used to manufacture them. While the aim of electrifying India's transport sector remains a core component of the net-zero ambition by 2070, the mineral demand due to 100% EV fleet will create enormous pressure on various materials including critical minerals. Therefore, it is crucial to understand various scenarios exploring different demand trajectories. The objective of this study was to estimate the demand for critical minerals required in passenger EVs for various net-zero scenarios created using the SAFARI model. The materials considered for this study include graphite, lithium, nickel, cobalt, manganese, phosphorus, and copper. These minerals have been listed as critical minerals by the Ministry of Mines owing to their high economic importance and risk of low supply (Ministry of Mines, 2023). They are the most sought-after materials used in various battery chemistries after being processed and refined into battery-ready materials. Three dominant battery chemistries were considered in this study: NMC, NCA, and LFP as described earlier in the methodology section. Table 2 highlights the applications of these critical minerals in specific battery components.

Table 2: Battery minerals and their applications

Mineral	Battery component	Applications
Lithium	Cathode	Lithium is the lightest metal and can store large amounts of energy. It acts as a very valuable component in a battery owing to its high electrochemical potential.
Nickel	Cathode	Nickel plays an important role in improving the energy density of a battery, which enhances the driving range while consuming less space in the battery.
Cobalt	Cathode	Cobalt helps enhance the energy density of a battery, especially when coupled with nickel, aiding in longevity and voltage stability.
Manganese	Cathode	Manganese is used in EV batteries to improve thermal stability, which helps reduce the risks associated with overheating during charging and discharging of batteries.
Phosphorus	Cathode	Phosphorus is used as a cathode in LFP chemistries, which are considered safe because they have a high thermal stability and offer more charge lifecycles.
Graphite	Anode	Graphite provides stability and allows a quick transfer of ions to and from the cathode because of its molecular structure.
Copper	Collectors	Copper is used for several critical components in lithium-ion batteries, including collectors and motors, because of its excellent electrical conductivity, chemical stability, and cost-effectiveness.

Sources: (Goonan, 2012); (Critical Raw Materials, 2023) (Stanford Advanced Materials, 2023); (Elgendy, 2024); (Ovrom, 2023)

4.1. Levers considered and their impacts

Table 3 explains the key intervention levers used to create scenarios in the model, and Figure 9 shows the impact of these levers on mineral demand. The impacts are shown as a percentage increase or decrease compared with the 2070 demand in a scenario without the intervention to better understand the importance of these levers. The mineral demand projected in the study is inclusive of minerals constituting imported batteries (current scenario) and domestically manufactured batteries (a potential pathway for self-reliance) to help examine India's total mineral demands irrespective of their source.

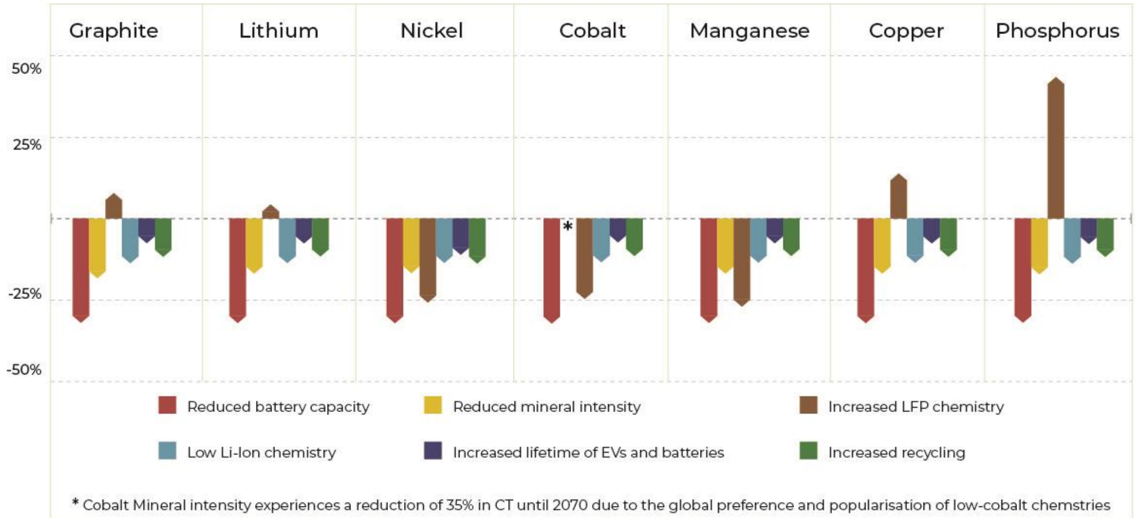
Table 3: Levers considered in the critical minerals module in SAFARI

Lever	Lever type	Description	Rationale
Reduced battery capacity (BC) by 20% by 2070	Behaviour	EV Battery capacity (equivalent of mileage for internal combustion engine car), signifies the amount of distance the vehicle can travel once it is fully charged.	Reduced BC (resembling lighter batteries and/or smaller vehicles) will reduce the need for critical minerals and the energy consumption of EVs to an extent, without significantly impacting daily urban commuters (due to smaller trip lengths). This lever would be applicable for a scenario wherein people consciously purchase lighter/smaller EVs.
Low lithium-ion chemistry (Low Li)	Technology	Decrease in the % share of lithium batteries over time and introduction of non-lithium batteries, such as sodium ion or redox batteries	The decrease in the lithium batteries stock over time will reduce the demand for lithium and other critical minerals because of the development of alternate battery chemistries without lithium.
Increased LFP chemistry (LFP) share to 60% by 2070	Technology	Making LFP battery chemistry dominant over NMC battery chemistry	The increase in LFP chemistry will reduce the reliance on nickel, cobalt, and probably, manganese. This lever will be triggered with the optimisation of LFP battery chemistries, motivating manufacturers to adopt it at larger scales.
Reduced mineral intensity (MI) by 20% by 2070	Technology	Decrease in the amount of minerals needed per kWh of battery	The decrease in the mineral intensity will lower the demand for critical minerals over time, applicable in a scenario with research on battery chemistries targeting to reduce the mineral demand through substitution or addition of other minerals.
Increased lifetime of EVs and batteries (LT) by 20% by 2070	Behaviour	Increasing vehicle and battery lifetime	Increasing battery and vehicle lifetime through conscious behaviour targeting proper maintenance, handling, and optimal charging reduces the demand for EVs and minerals.
Increased recycling rate to (Recy) 20%	Technology	Increasing annual recycling capacity for retiring EV stock	Increasing the recycling rate will ensure a secondary supply of minerals, thereby reducing mineral demand.

The lever with the maximum impact on mineral demand was increased LFP chemistry, which is a technology-driven lever that makes LFP chemistry the dominant battery type, accounting for 60% of the total lithium battery share by 2070. Some minerals such as nickel and copper saw a cumulative decrease in demand of

21%, whereas others such as phosphorus saw an increase of 38%. Advanced LFP chemistries provide a higher driving range, reduce the need for critical raw materials by a large portion compared with their counterparts, and typically use phosphorus and iron (some recent versions of the battery also include manganese). These batteries have increasingly become popular, especially for light EVs (IEA, 2023a), and may continue to garner research interest for improving battery efficiency and applicability in heavy EVs. However, phosphorus is also listed as a critical mineral because it is the primary material used in the fertiliser industry. Figure 9 shows that in an increased LFP battery chemistry scenario, although the demand for cobalt and nickel reduces by 21%–22%, the mineral requirement for graphite increases marginally by 5% because the mineral intensity of graphite for LFP batteries is higher. Phosphorus demand increases by 38% compared with the baseline. This could compete with the phosphorus demand for fertiliser use in the agriculture and food sectors and presents a trade-off with the continued reliance on high-risk materials such as cobalt and nickel. To counter the problem of low-energy density in traditional LFP batteries, manganese has been used in certain variations of LFP chemistries called Lithium Manganese Iron Phosphate (LMFP) batteries. These improve the energy density, are safer to use, and have a low cost (Mulgund, 2024). An increase in LMFP batteries will simultaneously lead to an increase in the demand for high-purity manganese (not included in this study).

Figure 9: Impact of levers on cumulative mineral demand by 2070



A 20% reduction in mineral intensities of the materials for different battery chemistries showed the second-highest impact. The assumptions for mineral intensities are provided in Appendix B. However, decreasing the mineral intensity, which is a technology-driven lever, indicates that battery chemistries utilising progressively lesser quantities of materials over the years can lead to a reduction in mineral demand by 13%–15% by 2070. This has been evident in various versions of NMC chemistries, which have varying mineral intensities for different materials across the chemistries owing to the replacement of other minerals and technological advancements.

Similarly, low battery capacity had a significant impact on mineral reduction across all minerals. This indicates that if battery capacities of vehicles decreased by 20% over time, mineral demand can be reduced by 20% by 2070. Increasing battery capacity implies that (a) the vehicles run longer when fully charged and (b) the size of vehicles is higher. However, this will not only lead to higher energy consumption to a certain extent (Poupinha & Dornoff, 2024) but also drive up the demand for critical minerals. Further, range anxiety is only to be experienced by long-distance commuters. On the other hand, urban commuters usually travel shorter distances, with only 2% of their total trips in a year being long-distance (Poupinha & Dornoff, 2024). A lower battery capacity trajectory, representing a behaviour-driven lever, implies that lighter vehicles are predominant EVs on road and that range anxiety, if at all, is taken care of through the provision of charging stations.

The impact of reduced share of lithium-ion battery on mineral demand over the years, which assumes the introduction of a non-lithium battery chemistry to contribute to 22% of the battery share by 2070, helps reduce mineral demand by around 11% for all minerals. This suggests that research on battery types such as sodium ion, zinc–air, and redox would have to be advanced enough to have proven commercial success and percolate the battery market.

A 20% recycling rate yields a 9% reduction in mineral demand for all minerals by 2070, which is much lower than the reduction resulting from other levers. The recycling of annual retiring EV batteries would have to be significantly higher to match up to the highest reducer's impact, requiring funding for advancement in research for refining processes and establishing recycling plants. Although few companies have ventured into battery recycling, overall, India lacks experience in battery recycling capabilities both on the policy and technological front (Bhattacharjee, 2023).

The enhanced lifetime lever, which is behaviour-driven, shows a 5% decrease in the cumulative mineral demand compared with the baseline. If the increase in lifetime is beyond 20%, mineral demand can be substantially impacted alongside other levers. Several factors affect vehicle and battery lifetime, such as usage, maintaining the right temperature, avoiding rapid charging, and using vehicles for longer durations of travel (EV Connect, n.d.).

4.2. Scenarios

Based on the levers in the SAFARI critical minerals module (listed in Table 3), we constructed the following scenarios (Table 4) to explore different pathways for transition to electric mobility and their impact on critical mineral demand.

1) **Current Trajectory (CT) Scenario:** This scenario is driven by the EV demand as defined by the current policies in place. The share of EVs in the total fleet by 2070 reaches around 30%–40% for 4Ws and buses and 70%–100% for 2Ws and 3Ws. Modal shares continue as per historical trends, focussing on more private and road-based travel.
2) **Technology Reliance (TR 10 / TR 20) Scenario:** This scenario assumes an ambitious 100% EV fleet (passenger) by 2070 with continuing CT modal shares.

There is a great focus on rigorous investments and funding for EV and battery technologies. The scenario comprises 10%–20% changes (TR 10 and TR 20, respectively) in the 'technology' levers.

3) **Eco-shift Transition (ET 10 / ET 20) Scenario:** This scenario assumes behavioural shifts both in terms of modal shares (more public transport in urban areas and increased use of railways for intercity travel) and preference for smaller vehicles. The scenario comprises 10%–20% changes (ES 10 and ES 20, respectively) in the 'behaviour change' levers. This scenario also assumes a 100% EV fleet by 2070.

4) **Technology Reliance + Eco-shift Transition (TR*ES 10 / TR*ES 20) Scenario:** This trajectory combines scenarios 2 and 3, embodying action on research and technology as well as consumer behaviour shifts. The scenario comprises 10%–20% changes (TR*ES 10 and TR*ES 20, respectively) in the levers.

Table 4: Scenario details

Lever	Techno-reliance	Eco-shift transition	Technology reliance + Eco-shift transition
Low battery capacity		✓	✓
Low lithium-ion batteries over time	✓		✓
High LFP battery chemistry	✓		✓
Reduced mineral intensity	✓		✓
Enhanced lifetime		✓	✓
Recycling	✓		✓

4.3. Results and discussion

Figure 10 shows the annual addition of passenger EVs across three scenarios—CT, TR, and ES. Compared with CT, TR shows the highest demand for vehicles across all modes because it considers a 100% EV fleet by 2070. ES is also a 100% EV fleet scenario; however, owing to the inclusion of public transport and higher reliance on rail for intercity and intracity travels, the demand for EVs in the ES scenario is less than that in the TR scenario. Appendix C provides a comparison of the SAFARI results with other studies.

Table 5 shows the range of mineral demand of all minerals in 2050 and 2070.

Figure 10: Annual addition of passenger EVs across Current Trajectory (BAU), Technology Reliance (TR), and Eco-shift (ES) scenarios

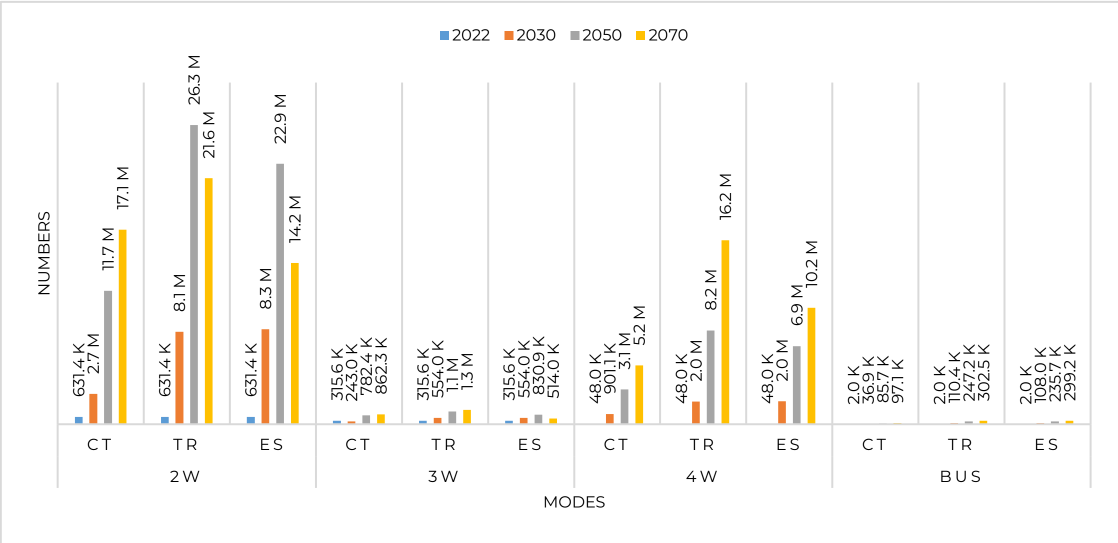


Table 5: Mineral demands for EV batteries as estimated in this study compared with IEA's global demand in the net-zero scenario (IEA, 2024a)

Mineral	Demand in 2050		Demand in 2070
	Current study (million tonnes)	As a share of IEA's global demand for EVs	Current study (million tonnes)
Graphite	0.32–0.67	5.3%–11%	0.4–1
Lithium	0.03–0.06	2%–4.6%	0.04–0.1
Nickel	0.12–0.26	5%–10%	0.12–0.3
Cobalt	0.02–0.03	5%–9.5%	0.01–0.03
Manganese	0.01–0.03	0.5%–1%	0.01–0.04
Copper	0.20–0.41	9.5%–21%	0.3–0.67
Phosphorus[a]	0.05–0.14	2.4%–6.3%	0.09–0.3

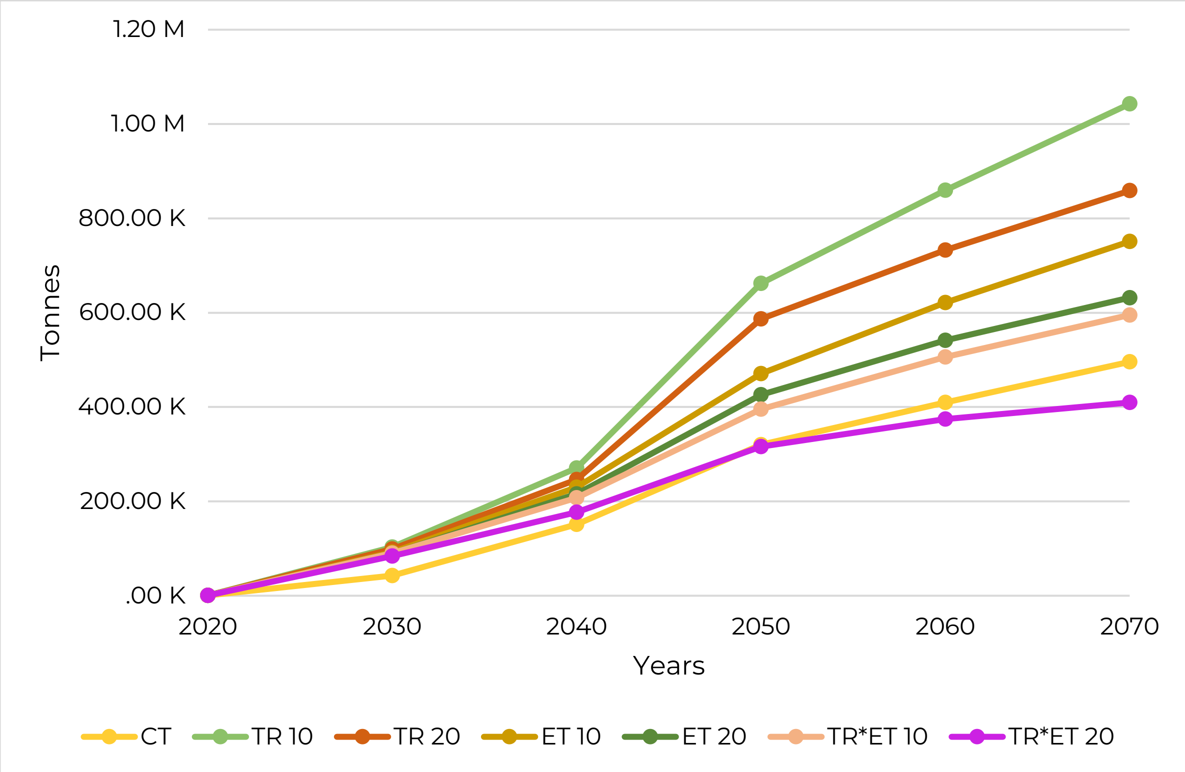
[a] Using the conversion factors: 1 kg phosphorus can be obtained from 2.29 kg phosphate and can be used to produce 3.16 kg phosphoric acid.

Mineral demand in both TR scenarios is much higher than that in the CT scenario because the former incorporates much higher on-road EV stock to reach 100% EV fleet by 2070 without significant modal shifts. The mineral demand in the ET scenarios is slightly higher than that in the CT scenario until 2060 and subsequently dips below CT levels because of a reduction in the number of EVs required owing to increased reliance on public transport and rail for intercity travel. This suggests that solely focussing on electrification of the transport sector may lead to a decrease in on-road emissions but will significantly increase mineral demand and associated emissions due to mining, processing, and refining activities. Therefore, it is crucial to consider the significant impact that public transport modes such as metro, non-motorised transport, buses, and rail can have on reducing EV numbers and drive down the demand for critical minerals. Lastly, the reduction due to the combined scenarios is phenomenal when compared with the ET and TR scenarios and surpass

BAU levels despite a 100% electrified fleet. Therefore, focussing on behaviour changes while continuing research and development for EVs and advancing battery technologies over time presents the best-case scenario, leading to absolute minimum reliance on critical minerals. Additionally, these mineral demands are only for the electrification of passenger vehicles and is bound to increase when accounting for freight vehicles. Because the contribution of national transport GHG emissions from freight and passenger vehicles are similar, the mineral demand required to decarbonise the former will be important to explore.

Figure 11 shows that among minerals, graphite has the highest demand across all scenarios owing to a very high mineral intensity as opposed to other minerals because of its use in the anode. Traditionally, graphite has been used in silos as anodes; however, current research is also exploring its addition or replacement with silicon, which can help provide better range and increase lifetime (Power, 2024). This will drive down the mineral intensity for graphite over time. However, such a shift will also lead to competition for materials because silicon is the primary mineral used in solar panels. In terms of access to the raw material, India has natural graphite reserves, but the availability of large flake graphite (required for the EV segment) remains unclear. However, several companies have ventured into synthetic graphite manufacturing, which may be emission intensive owing to the use of coke as a feedstock but can guarantee better performance than natural graphite. India currently imports graphite from China, Mozambique, and Madagascar (Ministry of Mines, 2023) and is also in talks with Sri Lanka to reserve mines (ET Bureau, 2024). Locally, a graphite block in Odisha was auctioned to private companies for exploration (PIB Delhi, 2024). Depending on the amount of battery-grade mineral that is available from acquiring local and international mines, India may be able to secure the graphite supply chain for the EV segment. The country also has the capacity for domestic processing of graphite anodes by virtue of some private companies. However, because the domestic demand for anodes is not very high (as most batteries are imported and not manufactured in the country), the capacity has not increased. The competition for graphite is high because of its use in several industries, such as aerospace, industrial, electronic, and automotive industries. Therefore, securing supply is a crucial move in case of graphite owing to the existing extent of raw material access and processing capabilities. Because material demand is the highest for graphite, as per current battery technologies, procuring the required amount through partnerships and exploration is key. Moreover, if mineral procurement can be coupled with scaling manufacturing capacity for graphite anodes, India may participate in international markets as a potential supplier in the future.

Figure 11: Graphite demand in the study scenarios



Lithium demand is the highest in the TR 10 scenario, crossing approximately 100K tonnes by 2070 (Figure 12). Sensitivity analysis for lithium also suggests that the demand for lithium can be reduced by increasing the market share of non-lithium batteries. Lithium is mainly used in EV batteries, and to a small extent, in other industries such as glass and pharmaceuticals, leaving the mineral exposed to less competition in comparison with other minerals. Lithium batteries will command the battery landscape for decades to come. Hence, building a resilient supply chain for lithium will be critical for India's EV transition. Currently, India imports most of the raw material from Chile, Russia, and China, among others (Ministry of Mines, 2023). A lithium block in the Katghora region in Chhattisgarh has been auctioned in February 2024 (PIB Delhi, 2024) and is set to open as India's first lithium mine (A. Kumar, 2024). As the quantity of lithium needed for 100% electrification scenarios is much lower than that of other minerals (owing to low mineral intensities in battery chemistries) and securing material through partnerships and exploration is already in process (owing to limited access to the mineral), it will be desirable for India to begin building its processing capacity to enable the regulated flow of battery-ready materials. Currently, India is in talks with other countries for help in lithium processing technology (Reuters, 2024).

Figure 12: Lithium demand in the study scenarios

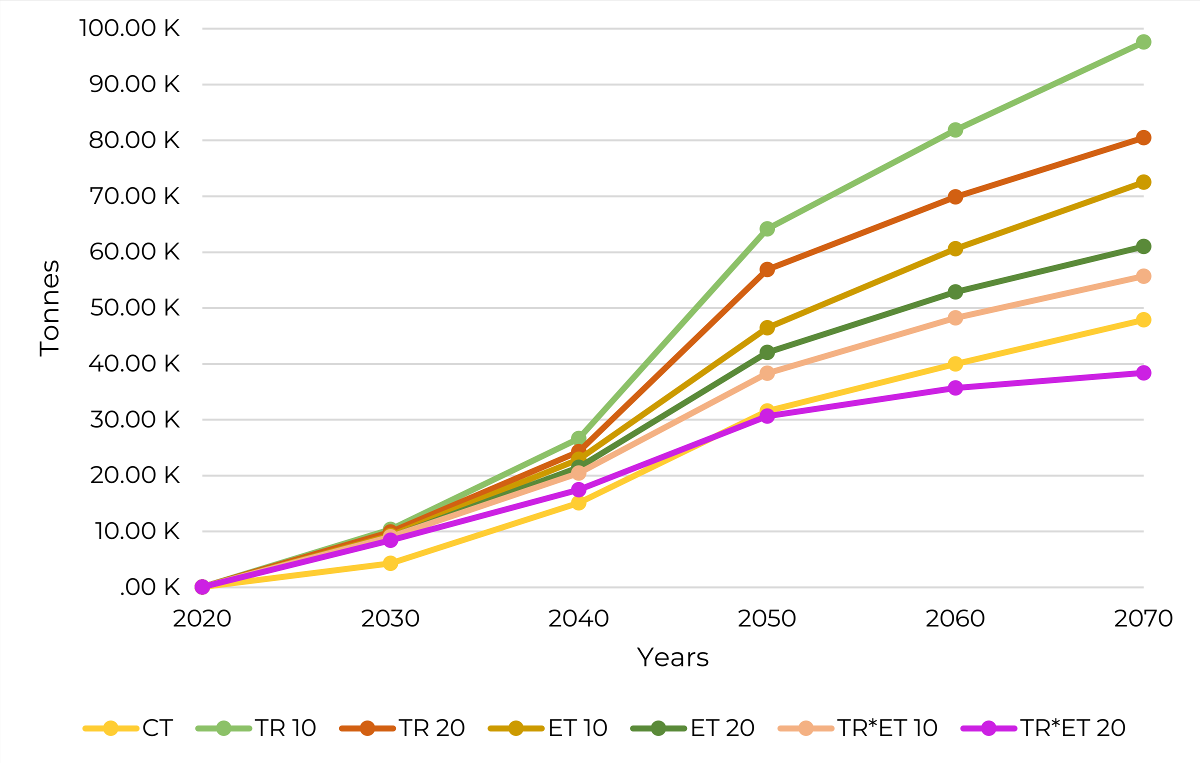


Figure 13 and Figure 14 depict that nickel, and cobalt demands are the highest under the TR 10 scenario and reach 300K tonnes and 32K tonnes, respectively, by 2070. In the combination scenario, nickel demand can be reduced to around 100K tonnes and cobalt demand to approximately 15K tonnes. India procures all its nickel from Sweden, China, Indonesia, Japan, and Philippines (Ministry of Mines, 2023) and has recently auctioned blocks of nickel in Bihar, Odisha, and Gujarat to private players (PIB Delhi, 2024). In addition, Odisha possesses 175 million tonnes of the raw material, contributing to 93% of the country's reserves; however, there is no domestic production of the material. India is also exploring deep-sea mining to detect nickel in the Indian Ocean through its project called *Samudrayaan* (Khanna, 2023). Because nickel is a core ingredient in NMC battery chemistries, it will be a very sought-after mineral in case of their dominance in the market. Furthermore, compared with lithium and cobalt, nickel's high mineral intensity in batteries drives up its volumetric demand. Nickel is also a pivotal material in steel manufacturing, making it competitive for the EV sector. India lacks any processing facility for battery-grade nickel. Thus, to develop and ramp up domestic battery production, partnerships and exploration to procure raw material will be crucial for setting up the nickel supply chain. These ties can be established with countries having access to more than one critical mineral, such as Indonesia, which has reserves for nickel, copper, and lithium.

Figure 13: Nickel demand in the study scenarios

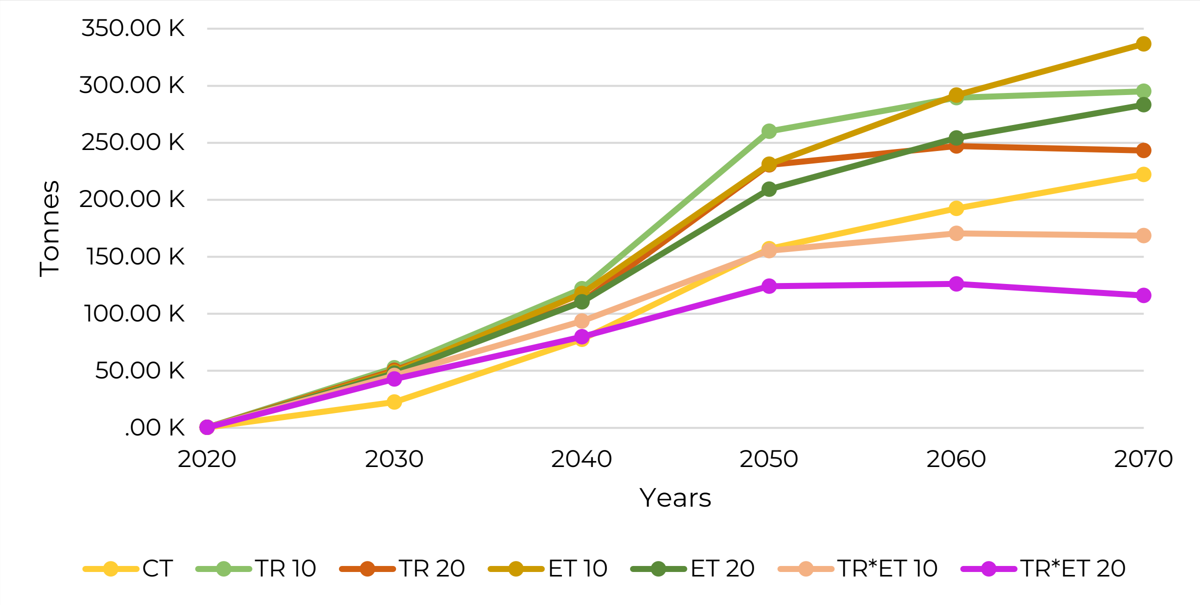
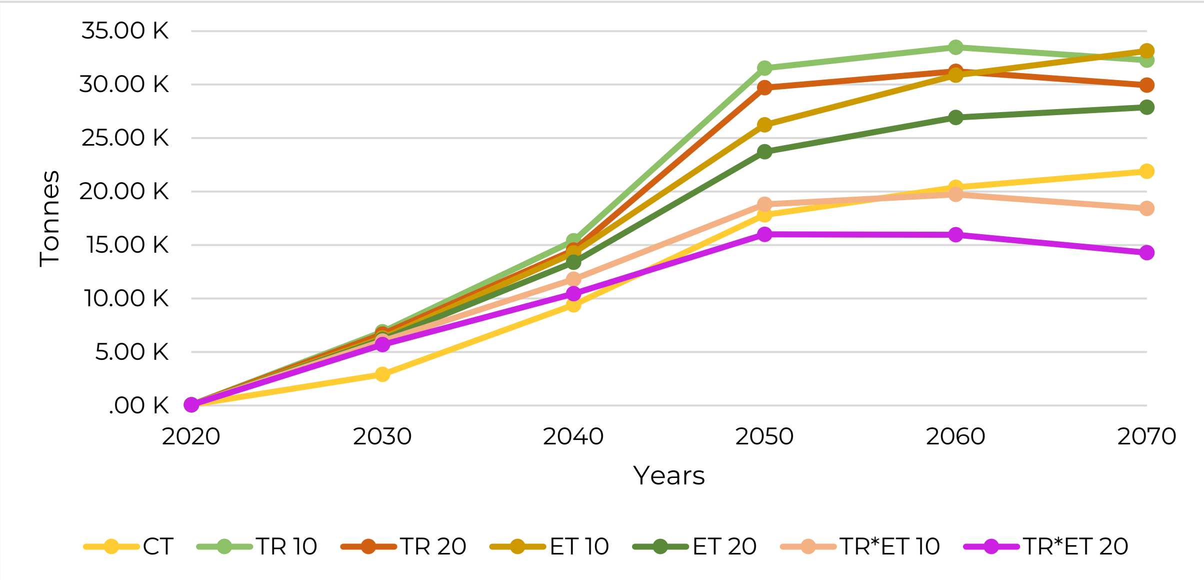


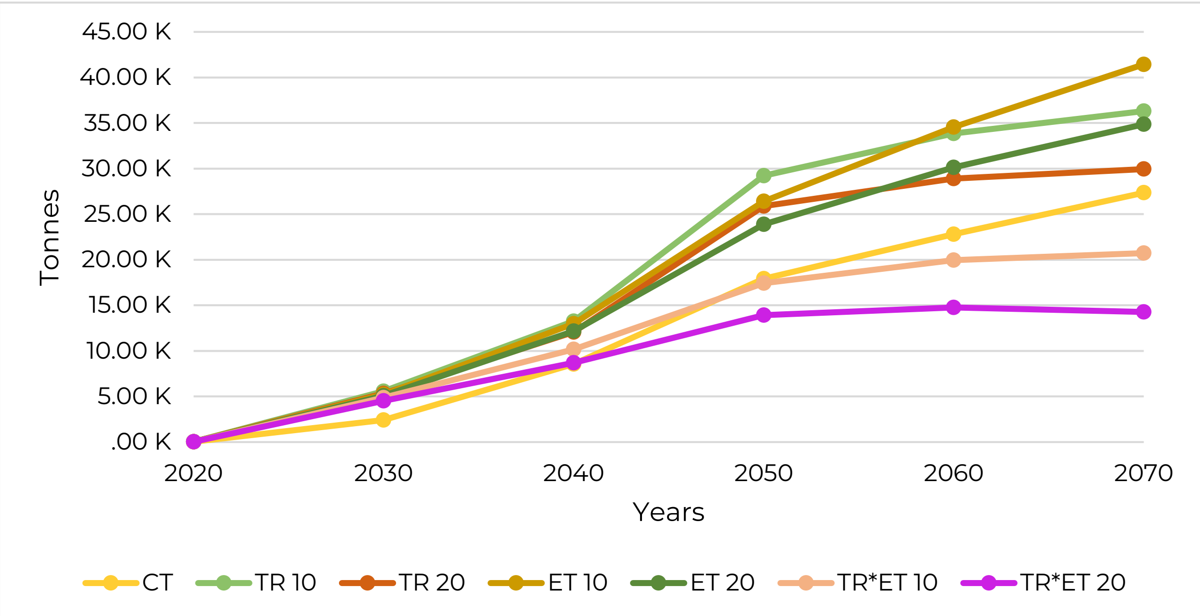
Figure 14: Cobalt demand in the study scenarios



Cobalt is used in several industries, including superalloys, ceramics, and paints (Lindner, 2024), but continues to be mainly used in batteries, making it less competitive for the EV sector. However, the raw material is majorly sourced from Congo (IEA, 2024a) and is mostly processed in China (Aktualisierung, 2023). India's main sources for cobalt imports are China, Belgium, and Netherlands (Ministry of Mines, 2023). Cobalt mining is often associated with several humanitarian issues (Amnesty International, 2023), which can be detrimental to an industry that is beginning to favour environmental, social, and governance compliances. This has resulted in an increasing tendency of manufacturers to opt for low-cobalt chemistries (Moors, 2022), such as NMC 811 (compared with its older counterparts such as NMC 622 and NMC 523). However, India is in the process of establishing a partnership with Congo to secure cobalt supply (KNN, 2024). In the likelihood of low cobalt demand driven by low and no cobalt NMC and LFP chemistries (especially in high LFP chemistry scenario), developing processing and refining capacities for the battery supply chain may be less important and directly securing the mineral by establishing partnerships with countries such as Indonesia and Congo may be more desirable.

Currently, the demand for manganese is attributed to NMC battery chemistries alone, and the demand shown in Figure 15 can be attributed to the dominance of NMC in the market share. In case of a higher LFP chemistry share, manganese demand can be significantly reduced. However, in case LMFP chemistries take off in the future, the demand for battery-grade manganese will increase. India has reserves of manganese ore in several states. However, the final product, i.e. high-purity grade of manganese known as high-purity manganese sulphate monohydrate (HPMSM) used in EV batteries, is unavailable in India. Further, the intermediate raw material required for manufacturing HPMSM, electrolytic manganese metal (EMM), is also not produced in India. EMM is produced from manganese ore through a fairly emission-intensive process; thus, to develop processing facilities for EMM in India, strategies for mitigating these emissions will be necessary (Zhang et al., 2020). Several companies are developing more efficient and comparatively less emission-intensive processes to make way for 'green' manganese (Cefai, 2023). However, owing to a lower volumetric demand for the material than that for other materials and its absence in traditional LFP chemistries, securing HPMSM directly through diverse partnerships with countries is seemingly a more strategic move than domestic production. In terms of competition, similar to nickel, manganese is dominantly used in the steel industry. This may not pose a problem if HPMSM is directly imported and the demand for EVs is fairly low owing to more reliance on other modes.

Figure 15: Manganese demand in the study scenarios



In terms of quantity, copper demand is the second highest after graphite, reaching as high as 67K tonnes in the TR 10 scenario by 2070 (Figure 16). Copper is used in several components in an EV and as a current collector in the battery. Because it is a highly popular and crucial material in several industries, the overall competition to secure copper for 100% electrification of the transport sector in India is extremely high. Copper also assumes a large share in the global demand for 2050, as reported by the IEA for the EV sector (Table 5), with the mineral demand under the TR 10 scenario being as high as 21% of the global demand. This contribution is from passenger EVs alone and would assume a significant share in the global demand when accounting for freight EVs. Copper is one of the most coveted materials across industries owing to its brilliant electric conductivity abilities; however, 40% of the mineral is consumed by the construction and infrastructure sector alone (ICRA, 2023), leading to high competition for the EV sector. Additionally, high electrification goals across industries to fulfil India's net-zero 2070 ambition will significantly drive up the material demand for transmission lines. Therefore, securing material supply for EV battery production is critical. Presently, India partially relies on imports for the raw material from countries such as Chile, Peru, Indonesia, and Australia (OEC, n.d.) and has some reserves in Rajasthan and Madhya Pradesh, with a recent block in Odisha being auctioned in early 2024 (PIB Delhi, 2024). Currently, India is in talks with Congo to secure copper supply (KNN, 2024). Moderate refining and processing capacities for copper exist in India, with the biggest producer having a 0.5 million tonnes capacity (PTI, 2024). In addition, another major copper refining plant with a 0.5M capacity per year has started its operations in Mundra, Gujarat, in early 2024 (PTI, 2024). In many applications such as wiring and collectors, copper can be replaced with aluminium but only in low-voltage lines. However, aluminium is a very emission-intensive material, despite being cheap and highly recyclable, which can drive up the embodied emissions of batteries. In contrast, copper is highly recyclable but maintaining scrap quality is important in ensuring material recovery (NewsVoir, 2024). Because of a strong foothold of the prevailing processes and raw material access coupled with copper's popularity in various industries, addressing the competition and securing the volumetric demand of the mineral for the EV industry are crucial to the material's EV supply chain. This further reinforces that the scaling of refining and recycling capacity for copper will play an important role in domesticating battery supply chains.

Figure 16: Copper demand in the study scenarios

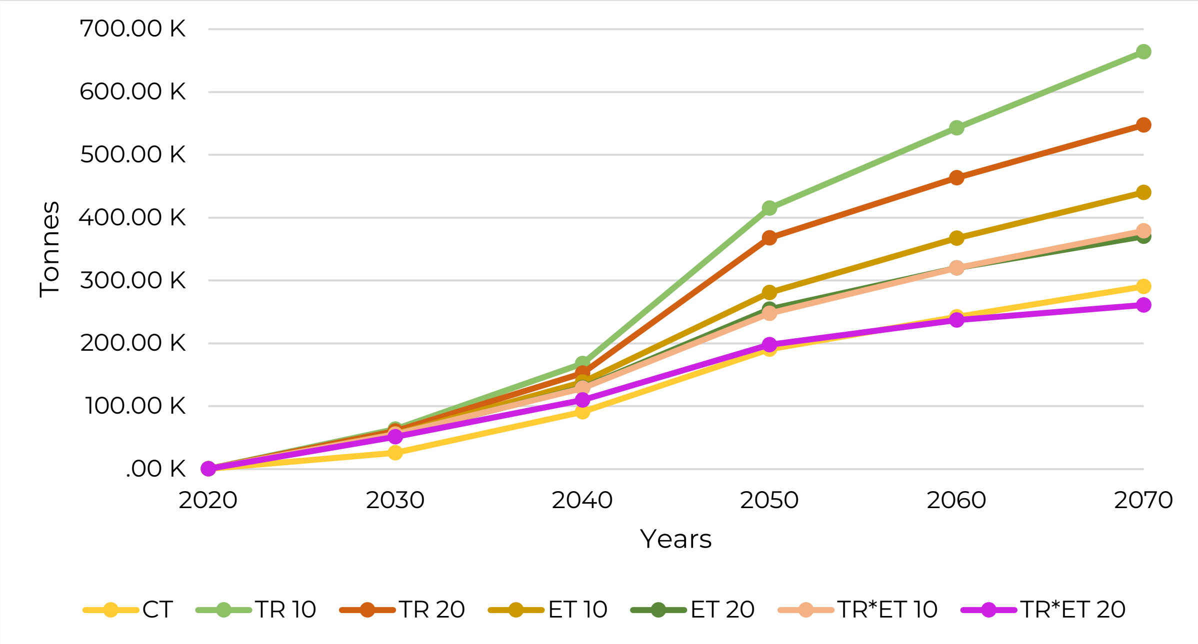
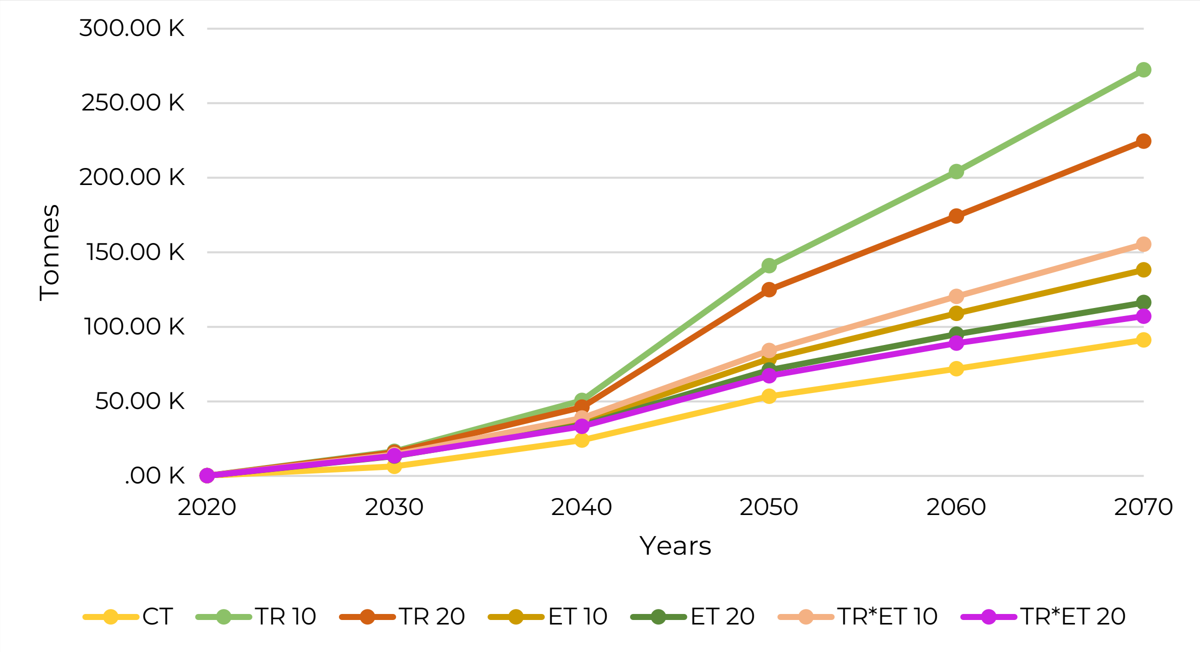


Figure 17 shows the maximum increase in phosphorus demand under the TR 10 scenario, crossing 270K tonnes, which accounts for 60% LFP chemistry dominance in the market by 2070. A further increase in the market share will significantly drive-up phosphorus demand. It is a key raw material used in LFP batteries and is derived from phosphoric acid, which is obtained from phosphate rock. India has around 3M tonnes of phosphate rock resources in Rajasthan, Madhya Pradesh, Uttar Pradesh, and Andhra Pradesh (PIB Delhi, 2021). Although the country still relies on imports for 90% of its feedstock, the government is considering exploration and mining activities in these states, with a block in Uttar Pradesh having been auctioned earlier in 2024(PIB Delhi, 2024). In the past 2 years, India has established long-term deals with several countries such as Morocco, Israel, and Oman and is considering new deals with Mauritania (Das, 2024). However, improving the access to raw material is encouraged to secure phosphorus for battery production, as currently, it is dominantly used in the fertiliser industry. Globally, India ranks third in terms of phosphate fertiliser production (Choudhary, 2024); therefore, competition for phosphorus between the food and fertiliser industries and the EV sector will be a key factor in strategising mineral allocation. This competition will especially intensify in the high LFP chemistry scenario, increasing the demand for phosphorus while reducing the reliance on nickel and cobalt. However, LFP batteries are easier to recycle than NMC ones and therefore can most likely ensure frequent secondary supply (Elcan Industries, n.d.). Although India has the required processing capacity to serve its mature fertiliser industry, refining processes and then scaling for battery-grade materials will be crucial aspects for domestic battery production. However, owing to high competition from the fertiliser and food industries, improved access and securing raw materials for batteries will be key areas to focus on.

Figure 17: Phosphorus demand in the study scenarios



Various demand trajectories have been identified through the scenarios presented in this paper. The EV industry is expected to advance in the country owing to various policies and incentives for original equipment manufacturers (e.g. Faster Adoption and Manufacturing of [Hybrid and] Electric Vehicles in India [FAME] and Production-Linked Incentive [PLI] schemes). It is crucial to understand the impact of such growth on critical minerals demand required for the transition and the competition for some of these minerals with other pertinent and growing industries such as agriculture and solar energy. The demand for these minerals for battery manufacturing may be met through imports, recycling, or indigenous manufacturing in local factories (motivated by the PLI scheme). However, these pathways present challenges in terms of global price volatility, availability of raw materials, domestic refining and processing capabilities, and technological advancements across the supply chain. One key course of action to address these supply challenges is to reduce the demand. This study analysed various levers and scenarios to manage EV and battery demands to lower the mineral demand through technology and behavioural shifts. The following measures are critical for mineral demand reduce:

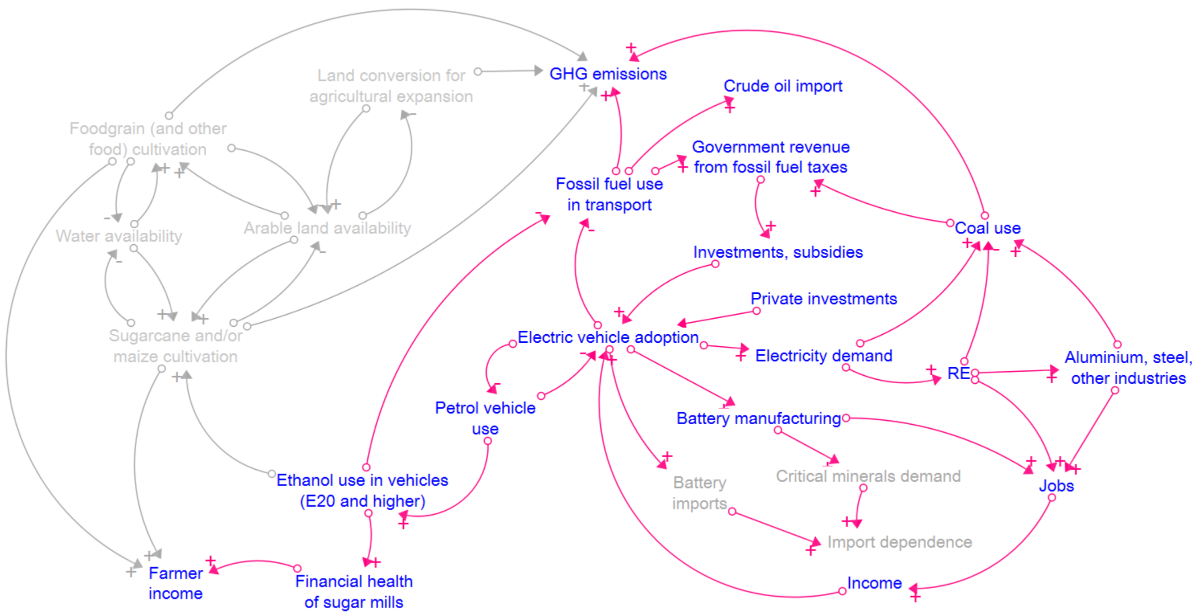
- Focussing on public transport modes for intracity travels
- Encouraging consumers to rely on rail for intercity travels
- Encouraging consumers to drive light EVs in addition to ensuring sufficient battery charging facilities to mitigate range anxiety
- Encouraging consumers to maintain battery and vehicle lifetime and focussing on technological research to improve these aspects
- Promoting research on alternative battery chemistries and battery recycling technologies and ensuring their commercial viability as well as optimising li-ion battery chemistries to use less critical raw materials.

Reduced mineral demand will not only aid in creating a self-sustainable EV supply chain but also help reduce costs due to material imports, making India resilient to sudden international price shocks or export bans and reducing the pressure on supply chains. While creating an indigenous battery ecosystem in the country will be beneficial, it is a long process involving various challenges in terms of raw material access, technological capabilities, policy support, and capacity building. Many aspects of the upstream supply chain also involve vigorous refining and processing activities, which will impact the energy and emission footprint of the industry. As this nascent industry expands and optimises, the most favourable lever to address supply challenges would be to manage the demand from various sectors to balance India's net-zero future and mineral needs.

Funded by the European Union

This activity is part of the European Union Climate Dialogues (EUCDs) project

5. Macroeconomic Impacts: Ethanol vs Electrification



Ethanol blending reduces crude oil import dependency, positively impacting the current account deficit. Its supply chain, involving agriculture, sugar mills, and petroleum refineries, is short, limiting growth impacts but easing implementation and boosting rural incomes. Electrification, driven by industries such as iron and steel, creates 3.3 times more jobs (compared with ethanol blending), mainly in urban areas, and can lead to a cumulative additional GDP of INR 13.4 lakh crore by 2030, compared with 2017. Combining electrification with grid decarbonisation further enhances GDP and employment through increased renewable energy investment. Recommendations include maintaining EV subsidies, investing in EV manufacturing and grid decarbonisation, and supporting ethanol blending to boost rural economies and overall development.

5.1. Scenarios

The scenarios set up for the SAM multiplier model were informed by the SAFARI transport module. The two key interventions currently being pursued by the government for transport sector decarbonisation in India can be categorised based on whether they impact the aggregate demand in the country or aggregate supply. Table 6 shows the key transport decarbonisation scenarios we analysed using TSAM. These scenarios are meant to isolate the macroeconomic impacts of specific interventions in the transport sector and identify the channels through which they are transferred to the whole economy from the transport sector. All impacts observed are in relation to the state and structure of the Indian economy as represented by the 2017–18 SAM employed for analysis.

Table 6: SAM scenario set-up

Policy	Scenario name	Scenario description
No Policy	No Policy	Increase in household petrol vehicle ownership No ethanol blending or electrification policy
Ethanol blending	Blending + Vehicle demand	Increase in household petrol vehicle ownership Increase in ethanol blending with petrol from 5% to 20%
Electrification of passenger transport	Partial electrification + Vehicle demand	Increase in vehicle demand EVs accounting for 45% of new 2Ws and 20% of new cars
	Partial electrification + Vehicle demand + RE	Increase in vehicle demand EVs accounting for 45% of new 2Ws and 20% of new cars Greener electricity grid: 45% coal, 10% solar, 4.% non-coal fossil fuel, 21% hydro, and 20% other nonconventional energy
	Electric vehicle (EV) demand	Increase in vehicle demand EVs accounting for all new vehicles

Both ethanol adoption and electrification of transport require significant investment. Therefore, the potential returns, i.e. the multiplier impacts of investment in specific sectors, need to be determined. Further, employment impacts should be examined to devise a strategy that ensures growth across labour classes and regions (rural and urban).

5.2. Results and discussion

No Policy

The No Policy represents a baseline or counterfactual scenario wherein petrol vehicle demand from households grows as it has historically, propelled by population growth and urbanisation trends, with no efforts towards electrification or ethanol blending. As a consequence, petrol demand increases, leading to a growth in industries along the vehicle and petrol manufacturing supply chains. Overall, 15% of the cost of production of vehicles is accounted for by iron and steel, with other metallic products accounting for 12.4% of the cost. As a result of higher vehicle demand in this scenario, the iron and steel sector expands by 3.46%, whereas the manufacture of other metallic products expands by 4.11%. Chemical products, crucial inputs to both vehicle and petrol manufacturing, witness a growth of 1.59%. The cumulative additional GDP growth in this scenario is 1.0%.

An additional 29 million jobs will be created under this scenario by 2030, driven by the significant (15.53%) growth in the vehicle manufacturing sector. This translates to 6 additional jobs created for every INR 10 lakh spent on the purchase of petrol vehicles. This sector alone accounts for 8.5 million of the total jobs created. Although the labour employed by the petroleum manufacturing sector is relatively small (9 workers per INR crore of output), it is one of the drivers of employment in this scenario, accounting for 0.6 million jobs.

Government revenue in this scenario grows by 1.5%, driven primarily by the increase in petrol consumption. This is because petrol taxes are a key source of revenue for the government; the contribution of taxes on crude oil and petroleum products to the exchequer has consistently increased from INR 1,72,054 crore in 2014–15 to INR 4,32,394 crore in 2023–24 (PPAC, 2024).

Blending + Vehicle demand

In 2017–18, 100% of the feedstock comprised molasses, a by-product of the sugar manufacturing industry. Ethanol production is strongly linked with the entire agriculture sector. In this scenario, the household ownership of petrol-based vehicles increased by 120%, in conjunction with SAFARI's E20 scenario in 2030. Ownership of only petrol-based 2Ws and cars changed, as the model assumed that the cost of purchase and consequent fuel consumption of buses and railway equipment are not directly borne by households. The share of non-EVs in the total vehicles owned by households remains unchanged. The household consumption of petrol increased by 115% (from 2017 to 2030) because of the increase in vehicle ownership.

In this scenario, the overall ethanol blending rate increased from the No Policy level of 5% (in 2017–18) to 20% (in 2030). The results from the multiplier model showed that this leads to an additional 1.8% of cumulative GDP growth or a 0.14% additional annual GDP growth by 2030. This translates to an additional GDP of INR 3.72 for every rupee of 20% ethanol-blended petrol sold.

Sectoral impacts: The agriculture sector grows by 3.03%, with sugarcane cultivation alone growing by 34% as a direct consequence of the higher blending percentage and higher total petrol demand from households' transport requirements. In contrast, the No Policy scenario witnessed a more modest increase of 1.24% in sugarcane cultivation owing to the absence of an ethanol blending policy. The higher petroleum demand in this scenario causes an increase in crude oil mining by 5.27%. To meet the increased demand for vehicles from households, the motorised vehicle manufacturing industry expands by 15.62%. This results in a proportionate increase (3.5%) in the iron and steel manufacturing sector, as iron and steel accounts for ~16% of the cost of production of motorised vehicles. This causes a 2.15% increase in iron ore mining. Electricity is a crucial input for both vehicle manufacturing and iron and steel sectors, accounting for ~6% and ~4% of the costs of production, respectively.

Accordingly, electricity generation increases by 2.3%. Electricity generation heavily relies on coal-based thermal power plants (82% of the total power generated). Furthermore, coal is an integral input in iron and steel manufacturing (19.5% of the total cost of production). A combination of these factors results in a 3.5% growth in the coal and gas mining sectors.

Impacts on employment: The agricultural sector is one of the most labour-intensive sectors in the country. Within this, sugarcane cultivation is one of the most labour-intensive, requiring 381 workers to generate INR 1 crore worth of output. In contrast, fossil fuel sectors, especially the manufacture of coke and petroleum products as well as non-coal–based thermal power generation, are among the bottom 10% of sectors in terms of labour intensity (ranging between 7 and 10 units of labour employed per INR 1 crore of output). This suggests that the ethanol blending policy, which would boost demand for sugarcane cultivation, would generate significant additional employment in the rural economy. From the Blending + Vehicle demand scenario, we observed that 18 million additional jobs can be created in sugarcane cultivation alone. An additional 2 million jobs can be created in the sugar/ethanol manufacturing sector, which employs 3.3 times more labour than petroleum manufacturing. Multiplier effects across the entire Indian economy can lead to an overall addition of 53.8 million jobs under this scenario, which is almost double the number of jobs created under the No Policy scenario. This makes the blending policy a good strategy to simultaneously tackle decarbonisation and rural employment goals in India.

Government: Although the ethanol blending mandate in this scenario aims to reduce the demand for crude oil, the significant increase in household ownership of petrol vehicles ultimately leads to a rise in government revenue (1.6%) similar to that under the No Policy scenario (1.5%). This is because the tax rate on petrol remains constant. Although less crude oil is used per litre of petrol, the overall fuel consumption increases because of the surge in vehicle ownership. Ethanol-blended petrol still incurs the same tax as regular petrol, offsetting the decrease in crude oil demand and maintaining the government's tax revenue.

Passenger Transport Electrification Scenarios

The demand-side intervention scenario deals with passenger transport electrification. For this intervention, we designed two sub-scenarios: (1) Partial electrification + Vehicle demand, wherein the total stock of vehicles owned by households and the share of EVs (both 2Ws and cars) increase, and (2) EV demand, wherein the stock of only EVs owned by households increases and the shares of 2Ws and cars remain unchanged. The assumption of households owning only 2Ws and cars remains the same. In the Partial electrification + Vehicle demand scenario, the total stock of vehicles owned by households rises (by 110% from 2017 to 2030), as population and urbanisation are expected to increase and cities are expected to expand in the future. We then altered the shares of EVs and internal combustion engine vehicles (ICEVs) constituting this stock; e-2Ws increase from 1.5% to 45% of the total 2Ws and e-cars increase from 0.04% to 20% of the total cars (Jain et al., 2022). Additionally, we ensured that the share of household demand for different fuels (petroleum, diesel, CNG, and electricity) associated with EVs and ICEVs changed in accordance with

SAFARI's 100% Passenger Transport Electrification Scenario (Table 7). In the EV demand scenario, only the stock of EVs owned by households rises (by 10% till 2030, according to SAFARI). As a result, household consumption of electricity changes, whereas the consumption of other fuels for transport remains constant.

Table 7: Change in fuel demand

Fuel type	Partial electrification + Vehicle demand	EV demand
Petrol	73	-
Diesel	91	-
CNG	300	-
Electricity	930	946

Partial electrification + Vehicle demand

In this scenario, we observed a cumulative increase in the GDP of 8.8% between 2017 and 2030, which is equivalent to 0.68% additional GDP growth per year.

An additional demand for petrol vehicles causes an increase in petrol demand. However, because we increased the share of EVs in the total vehicle demand from households, we ensured that an appropriate proportion of petrol demand is replaced by electricity demand from households. This will help boost the electricity sector.

We simulated a version of this scenario with a decarbonised power grid and found that GDP increases by 9.8%.

Sectoral impacts: There is a large increase in petrol demand (73%) under this scenario owing to higher vehicle ownership, and 5% ethanol blending in petrol in 2017–18 remains unchanged. This increases the demand for ethanol-blended petrol, which would also increase ethanol requirement, boosting sugarcane cultivation by 2.19%. Additionally, in this scenario, we increased the share of EVs in the total stock of vehicles owned by households. As a result, we increased the electricity demand from households (Table 7). With 82% of electricity sourced from coal-based thermal power plants in the No Policy scenario, the total demand for coal significantly increases, allowing the coal mining sector to expand by 35.6%. This also results in an increase in the manufacturing of coke oven products by 16.85%.

Despite the reduction in the share of petrol-based vehicles under this scenario, the petrol demand increases because of the absolute increase in petrol vehicle demand and the huge increase in electricity demand. Owing to a significant expenditure on petrol by the non-coal–based thermal electricity generation sector, the petroleum manufacturing sector scales up by 27%. The iron and steel sector expands by 10.4% because of the increased demand from the vehicle manufacturing sector and electricity sector. With a decarbonised power grid, iron and steel manufacturing grows much faster (at 15.72%) because of higher demand from the RE sector. This also boosts the demand for coal as the iron and steel manufacturing process is inherently dependent on coal.

Despite the significant increase in EV demand from households, the motorised vehicle manufacturing sector grows less than anticipated (by 15.7%). This is because EVs make up a very small percentage of household vehicle ownership (0.7%) and an even smaller percentage of the total vehicle demand in the economy (0.15%).

Impacts on employment: Strikingly, the employment generated in the Partial electrification + Vehicle demand scenario is over 3 times greater than that in the Blending + Vehicle demand scenario and over 6 times greater than that in the No Policy scenario. With the demand for petrol vehicles increasing, the petrol manufacturing sector sees a significant increase in labour demand and employs 2.4 million additional workers. Given the increase in electricity demand due to the higher share of EVs, the coal mining sector generates even more employment (2.7 million additional jobs). This translates to 0.2 million coal mining jobs annually, in the absence of grid decarbonisation. Coal-based electricity generation itself is highly labour intensive, employing 40 additional workers for every INR 1 crore of power generated. Consequently, in this scenario, this sector generates 36 million additional jobs, thereby accounting for the largest share of the total 176.5 million jobs created. If the transition is achieved by 2030, 13.6 million jobs will be created per year.

Of note, although coal-based power generation is the single largest employer of labour in the power sector, the labour intensity of the RE power sector (including hydro, solar, wind, biomass, and others) is 90 workers for every INR 1 crore of power generated. This is significantly higher than the labour intensity of total fossil fuel–based power generation, which employs about 49 workers per INR crore of power generated. Accordingly, the impact of grid decarbonisation in the Partial electrification + Vehicle demand scenario is significant. In total, 205.4 million jobs can be created between 2017 and 2030 in this scenario. Of these jobs, 26 million are directly created by RE power generation, which is more than double those created by fossil fuel power generation (9.55 million jobs).

Given that the majority of beneficiary industries in this scenario predominantly employ urban labour, it is probable that these employment opportunities will have a limited impact on the rural economy. This could exacerbate economic inequality between rural and urban areas and hinder balanced development across regions.

Government: In this scenario, government revenue surges by 8.3% from 2017 to 2030. This significant increase outpaces the 1.5% growth observed in the No Policy scenario. This is primarily due to the substantial increase in vehicle ownership, driven by population growth, urbanisation, and expanding cities, which leads to a higher demand for both electric and petrol vehicles. The substantial growth in the electricity sector, driven by the increasing adoption of EVs, is an important contributor to the overall increase in government revenue, as India has imposed a cess on coal since 2010 (IISD, n.d.). The higher output of coal in this scenario leads to a rise in coal tax revenue. This indicates the potential for the government to benefit from a balanced approach to energy transition.

With a decarbonised grid, government revenue increases by 8%. The growth is lower because the increase in coal demand does not compensate for the reduction in petrol demand in this scenario. As a result, the loss in revenue due to lower petrol tax collection is not fully offset by the higher revenue from the taxation of coal.

EV demand

In this scenario, we examined the economy-wide implications of increasing the stock of EVs owned by households. The share of electric 2Ws in the total household 2W demand rises from 1.5% to 45% and that of electric cars rises from 0.04% to 20%. Assuming India can achieve this passenger transport electrification target by 2030 (in line with the SAFARI 100% electrification by 2070 scenario), our multiplier results showed that this would lead to a cumulative increase in GDP by 7.8%. This translates to a 0.6% annual additional GDP growth between 2017 and 2030 solely due to this intervention. In other words, each rupee of EV sales could result in an increase in GDP of INR 230. This is an indirect result of increasing the number of ICEVs and EVs in the Partial electrification + Vehicle demand scenario, as opposed to increasing only the share of EVs in the EV demand scenario. The share of EVs in the total vehicle demand from households is minuscule (only 0.7%) in 2017. The overall increase in vehicle demand from households in the Partial electrification + Vehicle demand scenario overshadows the contribution of EV sales in the GDP. This contribution becomes apparent in the EV demand scenario, wherein only the stock of EVs demanded by households changes.

We simulated a version of this scenario that includes decarbonisation of the power grid and found that the GDP increases by an additional 1% (i.e. GDP growth in this scenario is 8.8%). More environmentally favourable sectoral impacts are described below.

Sectoral impacts: The increased demand for electricity fuels a substantial expansion in coal mining, with output growing by approximately 34% compared to the 2.16% growth in the No Policy (Table 8), in the absence of grid decarbonisation. Considering the thermal power sourced from non-coal fuels such as petroleum products grows to meet the rising electricity demand, the petroleum refining sector output also grows by 15%, despite the fall in petrol consumption of households. As shown in Table 8, the demand for iron and steel due to higher EV demand drives a 7.19% increase in the sector's output in the EV demand scenario.

However, the growth of iron and steel production in the EV demand scenario with a decarbonised grid is 1.7 times higher because of the upstream effect of increasing the RE share in the electricity grid. Iron and steel production accounts for about 58.5% of the total cost of production of solar-based electricity, making it a key input that benefits from grid decarbonisation.

The motorised vehicle manufacturing sector grows by 1.86%, which is much lower than the growth in the No Policy scenario. This is because EVs make up a very small share of the total vehicle manufacturing, whereas petrol vehicles account for a majority of the total output of motorised vehicle manufacturing and their demand grows significantly in the No Policy scenario.

Impacts on employment: Similar to the Partial electrification + Vehicle demand scenario, the key contributors to employment generation in this scenario are the power generation sectors, accounting for a total of 43.4 million jobs. The total increase in the number of workers employed in this scenario is 147.3 million (Table 9). Labour demand from the vehicle manufacturing sector grows much less owing to the small share of EVs in total motorised vehicle manufacturing. With grid decarbonisation, the growth of employment in this scenario is comparable to the Partial electrification + Vehicle demand scenario as 176.2 million additional workers are then demanded. This translates to 13.6 million additional jobs created per year between 2017 and 2030. However, as the model is currently unable to account for the role of imports in EV manufacturing, the actual employment generated domestically may be lower.

Government: Assuming India can achieve this passenger transport electrification target by 2030 (in line with the SAFARI 100% electrification by 2070 scenario), government revenue increases by 6.7%. This surge is primarily due to the substantial growth in the electricity sector, leading to increased tax collection. However, the revenue increase is not as significant as that in the Partial electrification + Vehicle demand scenario (Table 8), wherein both electric and petrol-powered vehicles saw a substantial increase in demand, resulting in higher revenue from both coal (due to higher electricity demand) and petrol. In the EV demand scenario, the focus is primarily on the growth of EVs, leading to a more concentrated increase in revenue due to higher coal-based electricity production.

Table 8: Comparative summary of growth impacts across scenarios

Sector	Impacts (% change compared to base year)			
	No Policy	Blending + Vehicle demand	Partial electrification + Vehicle demand	Partial electrification + Vehicle demand + RE
Coal mining	2.17	2.26	35.61	16.54
Iron ore	2.13	2.15	6.73	8.79
Coke and petroleum refining	6.71	1.54	27.24	22.23
Iron and steel manufacturing	3.46	3.52	10.39	15.72
Motorised vehicles	15.53	15.62	15.72	15.77
Government revenue	1.5	1.6	8.3	8.0
Cumulative GDP	1	1.8	8.8	9.8

Table 9: Comparative summary of employment impacts across scenarios (number of additional workers compared with 2017–18)

No Policy	Blending + Vehicle demand	Partial electrification + Vehicle demand	Partial electrification + Vehicle demand + RE
29.03 million	53.8 million	176.5 million	205.4 million

6. Conclusions and Transport Sector Decarbonisation Roadmap

A roadmap to decarbonise India's transport sector must consider the current policies and targets, including improved efficiency, electrification, ethanol blending, and modal shifts, while avoiding the negative impacts of land-use change and burgeoning critical raw mineral demand. Such a pathway will reduce transport sector emissions to ~266 $MtCO_2e$ in 2070, which is greater than a 70% reduction from current trends, thus aligning well with the 'net zero by 2070' action plan.

6.1. Conclusion

India is at the cusp of a clean energy transition and has the unique opportunity to plan a sustainable path with minimum trade-offs or unintended consequences. In the previous chapters, we discussed the resource and macroeconomic implications of the two key transport decarbonisation measures—electrification and biofuel use. The key highlights are as follows and summarised in Table 10.

6.1.1. Biofuels

Sustaining E20 with maize as an additional feedstock to sugarcane will considerably increase the demand for maize. As maize is a critical crop that is predominantly used as a livestock feed, its use for ethanol production will increase the demand pressure on the domestic production, which in turn could lead to food price inflation. Certain indications of this impact have already been observed with the start of maize use for ethanol production.

In the long term, the area under maize cultivation will have to be increased to sustain E20, even under the assumptions of higher maize yield. This could lead to faster depletion of fallow land currently available for agriculture area expansion. This, in turn, risks the conversion of other land-use types, such as forest land or land that could have been afforested into crop land to sustain E20. With growing urbanisation and RE, land is a critical resource for sustainable development, which must be fairly considered in our ethanol mandate.

Ethanol has a significant impact on rural livelihoods by boosting farmer incomes and providing other co-benefits of a sustainable means of managing sugar surplus while reducing crude oil imports and emissions.

The key, therefore, is to have an ethanol mandate that leverages the benefits and avoids the pitfalls of the additional demand for maize and sugarcane. Sustaining the E10 blend avoids significant land and water impacts associated with the E20 target, as E10 can be supported through the existing sugarcane cultivation without requiring additional land or infrastructure changes.

6.1.2. EVs

Transitioning to EVs is dependent on a sustainable critical raw material supply chain. Projections of a snowballing share of the global demand from India, particularly for materials such as copper, cobalt, and lithium, are indicative of a risky transition pathway. Therefore, demand management strategies for critical raw minerals are as important as securing supply for sustaining the EV transition.

Unlike the other demand segments of critical minerals such as power and electronics, the transport sector has a greater scope to benefit from consumer behavioural choices. Shifting to public transport modes is an effective means of reducing the burgeoning demand for critical minerals as well as energy and emissions.

The additional electricity requirement to shift from the Current Trajectory levels of electrification to 100% passenger vehicle electrification is negligible (~2% annually on an average). This is because the electricity demand from the transport sector continues to remain a small fraction of the total electricity demand. This, in turn, means that there is no additional pressure on RE and associated land requirement that is attributable to 100% passenger vehicle electrification. However, despite the negligible aggregate electricity requirement, we find that 100% passenger vehicle electrification translates to an average daily load of 6%. Currently, the peak load is already about 25% of the daily load. Depending on the timing of charging, the EV transition could potentially lead to additional requirement of peak power.

EV charging infrastructure poses a significant risk of increased pressure on urban land for parking and charging infrastructure, which could have cascading impacts on urban liveability and surging land costs (City Climate Finance Gap Fund, 2022; NITI Aayog, 2021a; ORF, 2024). Urban planning infrastructure that supports modal shift away from road-based individual vehicle modes to more rail- and NMT-based public transport choices can therefore additionally have the co-benefits of reduced congestion and pressure on urban land.

The EV sector has key linkages to manufacturing industries and electricity sectors and therefore drives greater economic and employment growth.

Table 10: Summary of the findings on ethanol blending and electric vehicles

	Ethanol blending	Electric vehicles
Trade-offs	Quicker uptake of fallow land posing increasing pressure to convert forest land Groundwater depletion from excessive sugarcane cultivation	100% electrification without any behavioural shifts to public transport or preference for smaller vehicles will increase the demand for critical minerals, for which India is import-dependent
Benefits	Efficient way to deal with sugar surplus and therefore improve the financial health of sugar mills (and in turn reduce arrears to farmers) Mild emission reduction potential	Significant emission reduction Air quality improvement Boosts the economy (GDP and employment growth)
Optimal way forward	Continue with E10 instead of E20, and use the surplus ethanol for bio-jet fuel production	Electrify vehicles in addition to promoting public and non-motorised transport and incentivise consumer preference for smaller vehicles

6.2. Roadmap Development

Considering these implications and trade-offs, we have charted a long-term strategy for decarbonising the transport sector.

First, we look at a **moderate decarbonisation scenario**, wherein the interventions to achieve decarbonisation are mostly driven by policy and regulations that are currently pursued.

Efficiency: India has enforced fuel-efficiency and emission standards, which are periodically updated for passenger and commercial vehicles to reduce fossil-fuel consumption and enhance energy efficiency in the transport sector. For passenger cars, the first phase of these norms ran from 2017 to 2022 and the second phase commenced in April 2022 and is expected to further reduce fuel consumption and emissions. In 2017, fuel efficiency standards for commercial vehicles including heavy-duty vehicles were also established. In SAFARI, under the CT scenario, a continual mild improvement of average efficiencies was assumed across all vehicular and fuel segments to reflect these policies. For the decarbonisation scenario, we assumed a more aggressive improvement in efficiency (5%–11% higher than that in CT over time), as summarised in Section 6.3. This has the potential of reducing annual emissions of the sector by up to 12% in 2070 compared with the CT scenario and cumulative emissions (2020–2070) by 3.6 gigatonnes of CO_2 equivalent ($GtCO_2e$).

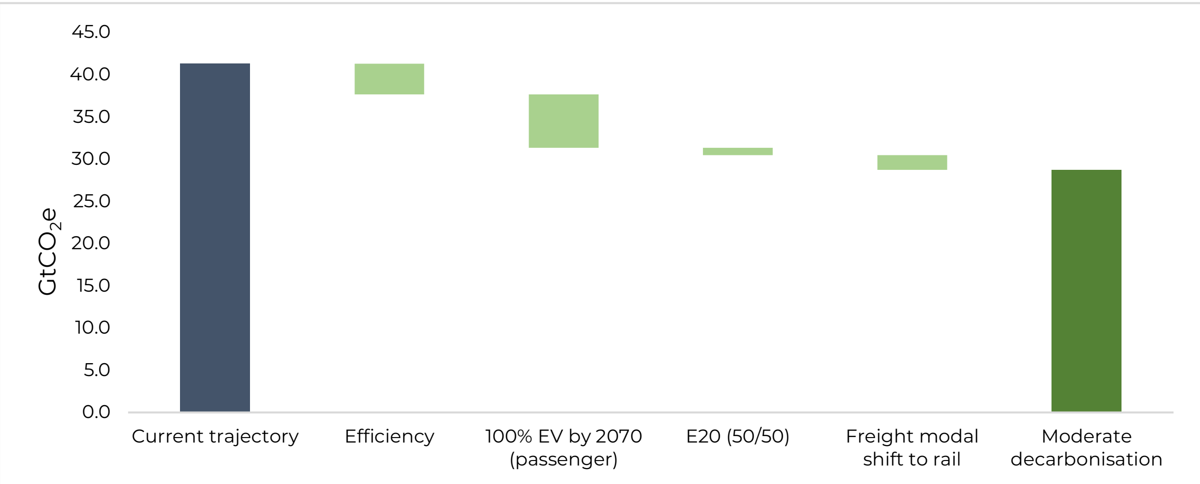
Electrification: India introduced the FAME scheme in 2015 to promote the adoption of hybrid vehicles and EVs. In 2018, the National Mission on Electric Mobility was launched, followed by the National E-Mobility Programme to encourage the public procurement of EVs and the establishment of charging infrastructure. The CT scenario assumptions were calibrated to historical EV adoption as per the VAHAN database and projected the continuation of those trends to the future. In the decarbonisation scenario, we assumed all passenger modes of transportation to progressively achieve full electrification by 2070 (net-zero year). This lever combined with efficiency has the potential of reducing the annual emissions of the sector by up to 45% compared with the CT scenario in the net-zero year and the cumulative emissions (2020–2070) by 7.3 $GtCO_2e$. As corroborated by several studies, we found that electrification is indeed the most effective mode of decarbonising the transport sector.

E20 (50/50): India aims to achieve the E20 target by 2025, which can also reduce crude oil imports, improve farmer incomes, and help manage surplus sugar. The national biofuel roadmap has assumed 50% of the ethanol production to be sourced from sugarcane and the remaining 50% from maize as a feedstock. While the CT scenario assumptions reflect the historical blending rates achieved, the future projections do not normatively achieve the E20 target. This scenario was thus designed to analyse the additional measures required to sustain the E20 blending rates in the future (sugarcane and maize in terms of feedstock and consequent land and water requirements) and the resulting mitigation potential compared with the CT scenario. In combination with efficiency and electrification, sustaining E20 can mitigate cumulative emissions by 1 $GtCO_2e$ (2020–2070).

Freight modal shift: Policy programmes such as Pradhan Mantri Gati Shakti - National Master Plan for Multi-modal Connectivity, Bharatmala Pariyojna, and Sagarmala as well as dedicated rail freight corridors aim to reduce the road share of freight transport and further optimise freight networks. Considering the growing freight transport demand, in the CT scenario, we assumed the trends in the current freight modal shares to continue; however, in the decarbonisation scenario, we assumed an increased share of rail (reaching 55% of total tkm by 2070), signifying a shift away from the road-based freight transport. In combination with efficiency, electrification, and E20, this lever reduces the annual emissions by 58% compared with the CT scenario. This translates to a cumulative emission mitigation of 1.8 $GtCO_2e$.

Cumulative emissions reductions of the levers discussed are provided in the waterfall chart in Figure 18.

Figure 18: Moderate scenario: Cumulative emission reduction waterfall chart

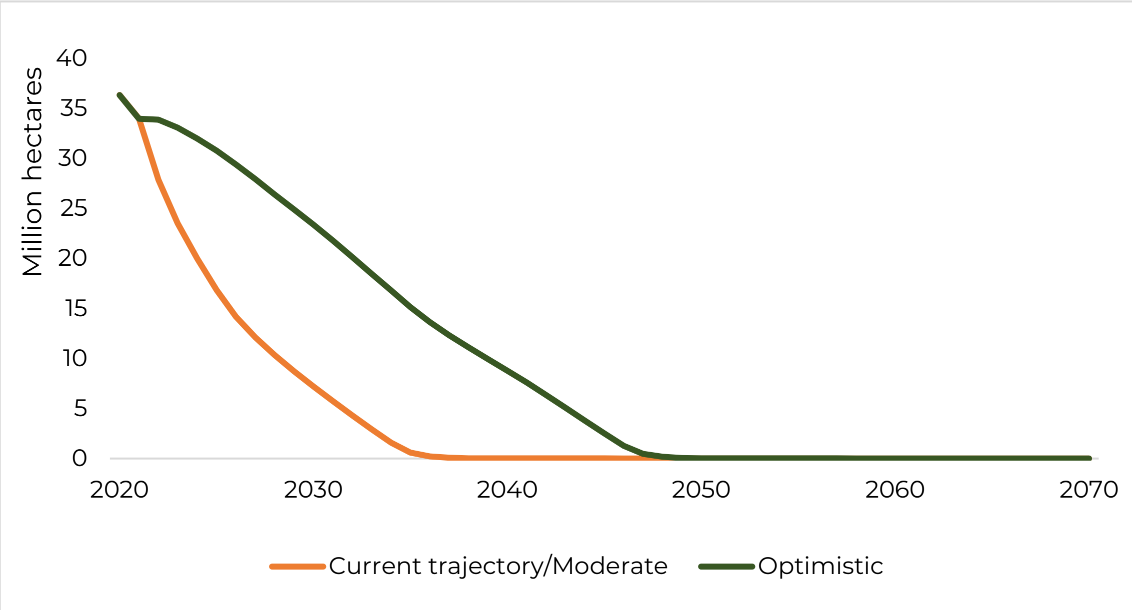


Next, we constructed a more **'optimistic' decarbonisation scenario**, wherein the trade-offs, as discussed in the previous chapters, are minimised.

Efficiency and Electrification: Same as the moderate scenario

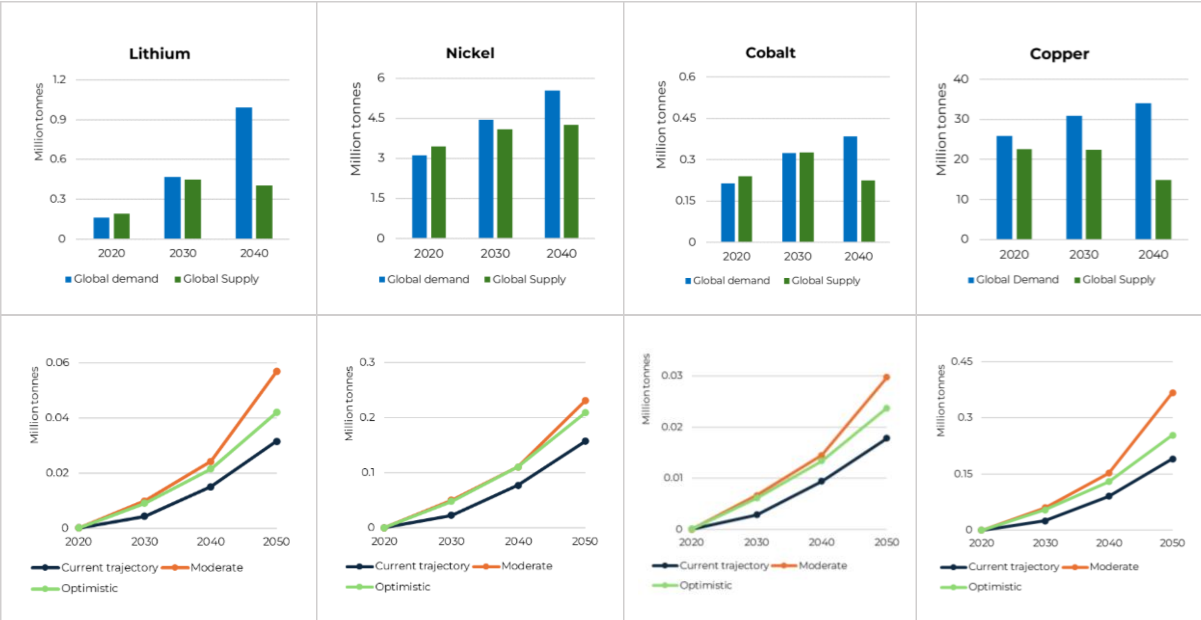
E10: This scenario assumes that a 10% blending rate is sustained, which is achievable with the existing sugarcane cultivation without requiring additional land or infrastructure changes. Sustaining E10, therefore, minimises the trade-offs in terms of land-use change (Figure 19) while retaining the opportunity to improve the rural economy and provide other co-benefits of ethanol blending. This lever, in combination with efficiency and electrification, reduces the annual emissions by 45% and can reduce the cumulative emissions from the sector by 0.2 $GtCO_2e$.

Figure 19: Fallow land under modelled scenarios



Modal shift: In addition to the freight modal shift, we considered modal shifts in the passenger transport, signifying a behavioural change, as detailed in Chapter 4. This lever unlocks significant emission mitigation potential, with an annual emission reduction of 63% (in combination with all previous levers) and a cumulative emission reduction of 3.1 $GtCO_2e$. As per the IEA's Global Critical Minerals Outlook, the global demand for lithium, nickel, cobalt, and copper outstrips the global supply by 2040 (IEA, 2024a). In the moderate scenario with a focus only on electrification, India's demand for these critical minerals will grow more steeply from 2040s till 100% electrification is achieved. With transport behavioural changes including modal shift, the mineral demand can potentially dip below CT levels (Figure 20).

Figure 20: (Row above) Global outlook for select critical minerals (Source: IEA). (Row below) Demand for the corresponding critical minerals from the electric vehicle sector under the modelled scenarios



Freight fuel shift: In this optimistic decarbonisation scenario, we assumed more radical fuel shifts, with more electric and hydrogen-fuelled vehicles in the freight segment, which is generally considered a hard-to-abate sector. This has a cumulative emission reduction potential of 1.9 $GTCO_2e$.

Sustainable aviation: Aviation is another hard-to-abate segment, for which we assumed the increasing use of bio-jet fuel in this scenario. The feedstock needed for producing the fuel in this scenario does not require any additional sugarcane area to be brought under cultivation, so it further boosts the ethanol economy without any land-use trade-offs. This has a cumulative emission mitigation potential of 0.5 $GTCO_2e$.

The cumulative emission mitigation potential (2020–2070) for this pathway is 16.4 $GTCO_2e$ (Figure 21), which is an additional potential of ~4 $GTCO_2e$ compared with the moderate scenario. Figure 22 shows the annual emissions under the modelled scenarios. In the net-zero year (2070), transport sector emissions in the moderate scenario, which assumes the effective implementation of current policies and trends, are reduced to 432 million tonnes of CO_2 equivalent ($MtCO_2e$), which is 56% below CT levels. In the optimistic scenario, with more ambitious targets and minimal cross-sectoral trade-offs, the emissions are further reduced by 38% to reach 266 $MtCO_2e$. The residual emissions are hard-to-abate and will need to be neutralised with natural or artificial carbon sinks.

Along with the net-zero goal, India has committed to increasing its forest carbon sink by 2.5–3 $GtCO_2e$. With the optimistic decarbonisation pathway, the transport sector will require only 9%–11% of the net natural carbon sink to reach net-zero emissions.

Figure 21: Optimistic scenario: cumulative emissions

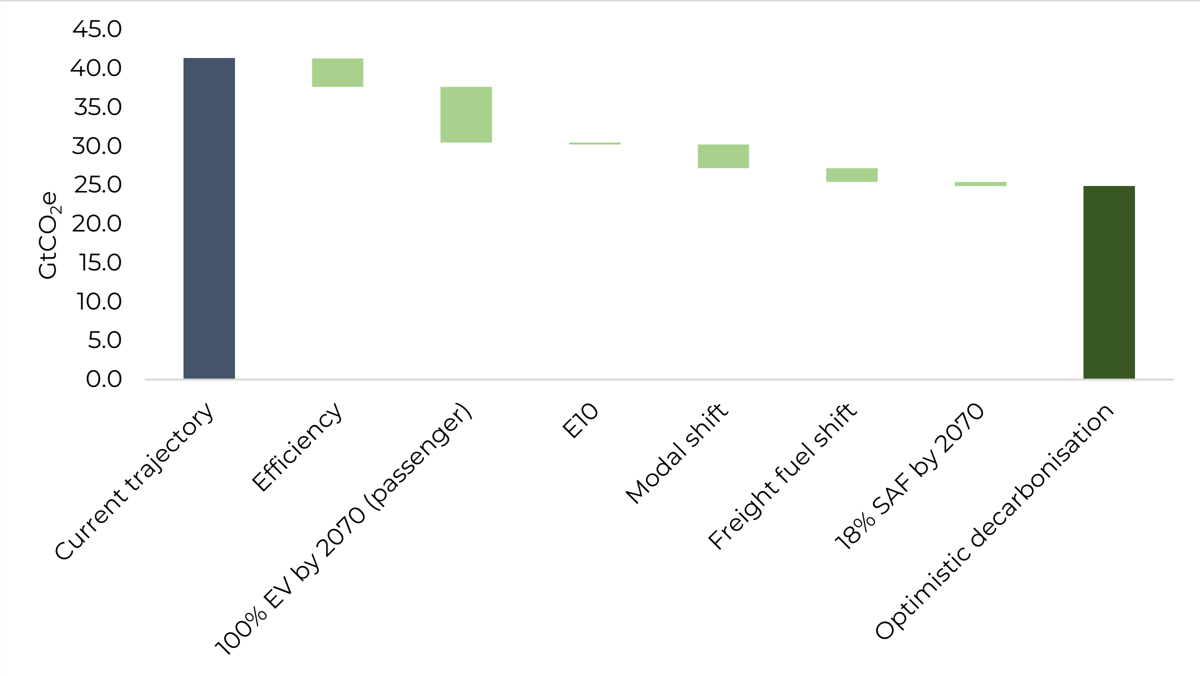
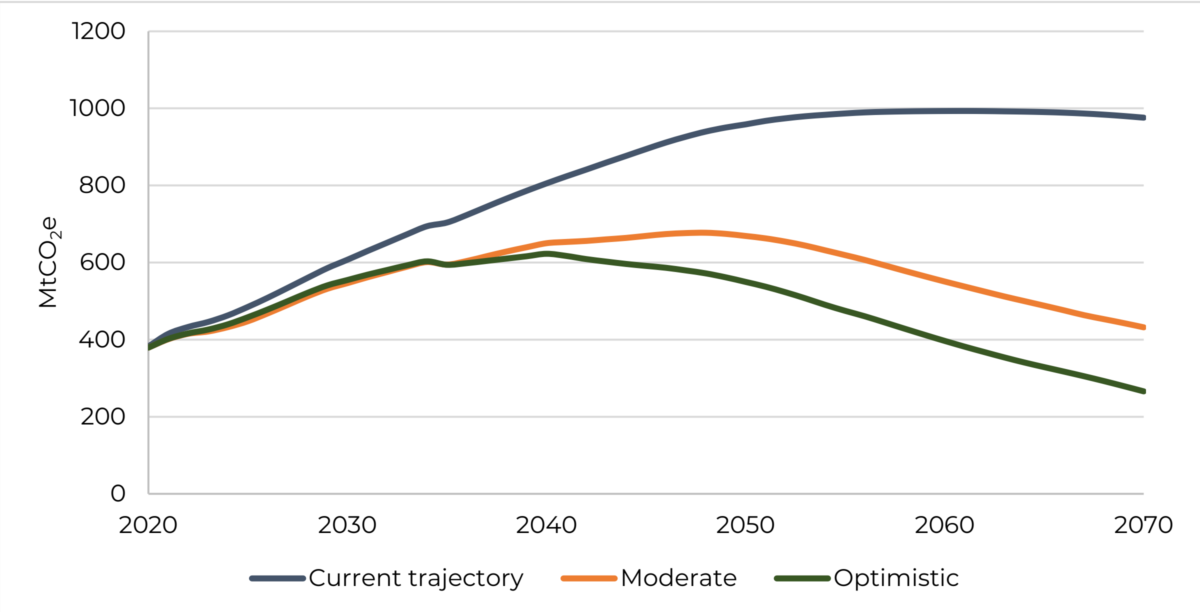


Figure 22: Annual transport sector emissions



6.3. Policy Roadmap and Implications

India's LT-LEDS document emphasises the development of an 'integrated, efficient, inclusive, low-carbon transport system' and comprehensively covers the current policies and strategies for the transition. The interventions accounted for in the optimistic scenario are in line with these policies and strategies. In this section, we conceptualise a roadmap for the optimistic decarbonisation scenario, which could be useful for setting a long-term direction and concretising specific targets so that the transport sector is in line with the net-zero action plan. A detailed roadmap for the optimistic decarbonisation scenario is provided in Figure 23.

The LT-LEDS document mentions that while the vehicular ownership has been picking up at a compound annual growth rate of 10% (2000–2019), the total vehicular penetration is only 32/1000 person, which is very low compared with developed countries and other emerging economies. This is a trend that is assumed to continue in our 'current trajectory', wherein the transport demand shifts increasingly towards more private modes. In the optimistic scenario, although this trend of increase in vehicular ownership is accommodated until the mid-term (2050), the balance shifts towards public transport for urban mobility during 2050–2070 to unlock deep decarbonisation. Similarly, the roadmap envisages a more stringent fuel emission regulatory regime, which can not only help optimise fuel savings but also help fast-track fleet electrification. The recommendation of creating a feedstock-production–linked dynamic ethanol mandate avoids the land- and water-related trade-offs. It also helps ensure the use of biofuels as a bridge to zero-emission vehicles or EVs, thus avoiding any infrastructural lock-in that might risk setting back the electrification. A complete list of policy actions and target indicators, towards the achievement of the roadmap is provided in Table 11.

Figure 23: Optimistic scenario roadmap

2030	2040	2050	2070
- Efficiency standards improvement over Current Trajectory (CT) by 5% - 1.7 times more annual EV sales than CT - Increase in rail share of intercity passenger transport by 2% over CT - 40 GWh battery recycling capacity - 10% CNG fuelled trucks - E10 blending mandate	- Efficiency standards improvement over CT by 8% - 90% more annual EV sales than CT - Increase in rail share of intercity passenger transport by 4% over CT - 90 GWh battery recycling capacity - 15% CNG fuelled trucks - E10 blending mandate	- Efficiency standards improvement over CT by 11% - 78% more annual EV sales than CT - Increase in rail share of urban transport by 2% and intercity passenger transport and freight transport by 10% over CT - 120 GWh battery recycling capacity - 33% CNG, 5% electric and 5% H_2 fuelled trucks - E10 mandate and 15% biojet fuel share in aviation	- Efficiency standards improvement over CT by 11% - 15% less annual EV sales than CT due to increasing shift towards public transport - Increase in rail share of urban transport by 5%, intercity passenger transport by 20% and freight transport by 25% over CT - 120 GWh recycling capacity - 70% CNG, 15% electric and 15% H_2 fuelled trucks - E10 mandate and 18% biojet fuel share in aviation

Using robust quantitative modelling techniques, our study emphasises India's two key transport decarbonisation strategies: biofuel use and electrification. The results underscore the need for minimising trade-offs, such as land-use change and unmanageable critical raw mineral demand in pursuing these strategies. The study further recommends a policy roadmap to decarbonise India's transport sector in a manner that can potentially minimise these negative impacts. Going forward, our goal is to continually improve our cohort of models to inform the decision-making process so that the energy transition is sustainable, well-designed, and capable of meeting climate targets.

Table 11: Policy directions

Key stakeholder	Action	Target indicator	2030	2040	2050	2070
Ministry of Petroleum and Natural Gas (MoPNG)	Create a feedstock-production–linked dynamic ethanol mandate for blending with petrol in the short term and for bio-jet fuel production in the long term	Ethanol production for fuel use with minimal land use and groundwater trade-offs	10 billion litres (E10)	12 billion litres (E10 and 15% blending with jet fuel)	14 billion litres (E10 and 16% blending with jet fuel)	14 billion litres (18% blending with jet fuel)
Ministry of Railways and State Governments	Measures to increase the intercity passenger transport share in the long term through continued investments in modernisation, high speed rail corridors, other capacity and service improvements, and leveraging multimodal connectivity opportunities	Share of railways in intercity passenger travel (% improvement over the current trajectory [CT])	20% (2%)	20% (4%)	25% (12%)	30% (20%)
	Continued infrastructure investments in increasing rail share of freight beyond 2050	Freight share of railways (% improvement over CT)	35%	35%	40% (5%)	60% (25%)
Ministry of Housing and Urban Affairs (MoHUA)	Urban planning to enable more walking, cycling etc. and continued investments towards enhancing convenience and adoption of public transportation in the long term	Urban public transport (bus+metro+NMT) share (% improvement over current trajectory)	55%	47%	53% (6%)	65% (28%)
Ministry of Heavy Industries	Continuing FAME scheme to enable more electrification of public transport and overall EV adoption with charging infrastructure	Boost in annual sales of electric passenger vehicles (2W, 3W, cars, and buses) compared to current trajectory	1.7 x	90%	78%	-15%
Ministry of Finance	Continuing tax incentives (purchase and road) and low-interest loans for increased uptake of electric cars over ICE					
	Measures like reduced GST for EV battery and continued PLI schemes to help achieve price parity with ICE					

Key stakeholder	Action	Target indicator	2030	2040	2050	2070
Ministry of Road Transport and Highways (MoRTH)	Purchase subsidy/incentives for scrapping/exchanging old ICE vehicles for EVs					
Bureau of Energy Efficiency (BEE) and Ministry of Road Transport and Highways (MoRTH)	Tighten emission standards and ensure compliance with complementary measures such as vehicular labelling	Overall emissions norms as a % improvement over CT	7%	18%	25%	40%
		Emissions norms for passenger cars in particular	68.5 gCO_2/km (BEE proposed [2027–2032] norm is 91.7)	51 gCO_2/km (BEE proposed [2032–37] norm is 70)	30 gCO_2/km	0
Ministry of Heavy Industries	Enhanced production-linked incentives for recycling entities	EV battery recycling operational capacity	12 GWh	42 GWh	92 GWh	150 GWh
Ministry of Environment, Forest and Climate Change (MoEFCC)	Effective implementation of the Battery Waste Management Rules, 2022, to enhance recycling rate					
Ministry of Mines (MoM)	Recovery potential of recycling critical minerals from used batteries to be factored in the critical mineral policy					

The Paris Agreement aims to keep global warming below 1.5–2°C above pre-industrial levels. As a signatory to the treaty, India has demonstrated its commitment to addressing climate change even while grappling with developmental challenges.

Among its updated Nationally Determined Contribution (NDC) targets, India has committed to achieving a 45% reduction in its emission intensity compared with 2005 levels by 2030. The country also aims to achieve its net-zero target by 2070. The Paris Agreement principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) allows India flexibility to account for hard-to-abate sectors that are expected to grow and resource constraints such as land and to pursue basic developmental goals while formulating a comprehensive decarbonisation strategy.

These dynamics are particularly relevant to transport sector decarbonisation because India's anticipated growth in population and urbanisation is expected to drive the demand for vehicle ownership and transport services. With road transport contributing 12% to India's annual energy-related emissions (IEA 2023), policies to reduce the fossil fuel-intensive nature of this sector are vital to achieving India's net-zero target and staying aligned with the goals of the Paris Agreement.

Our study goes beyond examining the mitigation potential of decarbonisation strategies for the transport sector and assesses the inter-sectoral impacts of transport decarbonisation policies on natural resources and import dependency. Our roadmap (Figure 23) proposes a combination of fuel efficiency, modal shift, electrification, and ethanol blending measures to make India's existing transport sector policy landscape even more Paris-compliant.

Our analysis shows that for the transport sector, continuing along the current trajectory under the existing decarbonisation policies would lead to cumulative emissions of 41.3 GtCO_2e by 2070. However, the analysed decarbonisation scenarios would allow India to free up between 12.6 and 16.4 GtCO_2e of the remaining carbon budget, which could potentially reduce the burden on other hard-to-abate industries.

The transport decarbonisation roadmap proposed in this study is aimed at achieving India's NDCs, considering the risks and resource constraints associated with the sector. The inter-sectoral and natural resource dynamics explored here enable a more nuanced understanding of India's mitigation capabilities and help place it in the context of both the CBDR-RC principle and temperature goal of the Paris Agreement.

7. References

Aktualisierung, L. (2023, May). *China domineates global cobalt production*. https://table.media/en/china/sinolytics-radar/china-dominates-global-cobalt-production/

Amnesty International. (2023, September). *Democratic Republic of the Congo: Industrial mining of cobalt and copper for rechargeable batteries is leading to grievous human rights abuses*. https://www.amnesty.org/en/latest/news/2023/09/drc-cobalt-and-copper-mining-for-batteries-leading-to-human-rights-abuses/

Ashok, K., Natarajan, R., Kumar, P., Sharma, K., & Mathur, M. (2021). Sustainable alternative futures for agriculture in India—The energy, emissions, and resource implications. *Environmental Research Letters*, *16*(6), 064001. https://doi.org/10.1088/1748-9326/abf0cd

Bhattacharjee, A. (2023, February). *EV battery recycling in India – Opportunities and challenges*. https://cleanmobilityshift.com/ecosystem/ev-battery-recycling-in-india-opportunities-and-challenges/

Bhutada, G. (2022, May). *The Key Minerals in an EV Battery*. https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/

Byravan, S., Ali, Mohd. S., Ananthakumar, M. R., Goyal, N., Kanudia, A., Ramamurthi, P. V., Srinivasan, S., & Paladugula, A. L. (2017). Quality of life for all: A sustainable development framework for India's climate policy reduces greenhouse gas emissions. *Energy for Sustainable Development*, *39*, 48–58. https://doi.org/10.1016/j.esd.2017.04.003

Cefai, S. (2023). *Long road ahead for 'green' manganese metal*. https://www.fastmarkets.com/insights/long-road-ahead-for-green-manganese-metal-market/

Central Statistical Organisation. (2008). *National Industrial Classification [All Economic Activities) 2008*. Ministry of Statistics and Programme Implementation Government of India.

Central Statistics Office (Industrial Statistics Wing). (2011). *National Product Classification for Manufacturing Sector (NPCMS), 2011*. Ministry of Statistics and Programme Implementation Government of India.

Central Statistics Office (Industrial Statistics Wing). (2020). *Annual Survey of Industries 2017-18*. Ministry of Statistics & P.I, Govt. of India.

Chen, L., Debnath, D., Zhong, J., Ferin, K., VanLoocke, A., & Khanna, M. (2021). The economic and environmental costs and benefits of the renewable fuel standard. *Environmental Research Letters*, *16*(3), 034021. https://doi.org/10.1088/1748-9326/abd7af

Choudhary, S. (2024, March). *Top Fertilizer companies in India*. https://timesofagriculture.in/top-fertilizer-companies-in-india/

City Climate Finance Gap Fund. (2022). *IMPLICATIONS OF ELECTRIC VEHICLES FOR URBAN PUBLIC SPACE*. https://www.citygapfund.org/sites/default/files/2023-03/221227-gap-fund-technical-notes-primer.pdf

Clean Mobility Shift EV Dashboard. (n.d.). [Dataset]. https://cleanmobilityshift.com/ev-dashboard/

Critical Raw Materials. (2023, October). *The role of Nickel in EV battery manufacturing*. https://www.innovationnewsnetwork.com/the-role-of-nickel-in-ev-battery-manufacturing/38877/

CSTEP. (2020). *Energy and Emissions Implications for a Desired Quality of Life in India*. https://cstep.in/projects-details.php?id=1099#:~:text=SAFARI%20can%20help%20policymakers%20visualise,in%20a%20bottom%2Dup%20manner.

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

CSTEP, CEEW, IRADe, PNNL, & TERI. (2019). *Comparison of Decarbonisation Strategies for India's Land Transport Sector: An Inter Model Assessment*. https://shaktifoundation.in/wp-content/uploads/2019/11/Intermodel-Study_Final-Report.pdf

Das, P. (2024, February). *India to sign long-term deal for buying key fertilizer input from Mauritania*. https://www.livemint.com/news/india-set-to-sign-fertilizer-import-deal-with-mauritania-11708507232097.html

Dhar, S., Pathak, M., & Shukla, P. R. (2017). Electric vehicles and India's low carbon passenger transport: A long-term co-benefits assessment. *Journal of Cleaner Production*, *146*, 139–148. https://doi.org/10.1016/j.jclepro.2016.05.111

Dhar, S., & Shukla, P. R. (2015). Low carbon scenarios for transport in India: Co-benefits analysis. *Energy Policy*, *81*, 186–198. https://doi.org/10.1016/j.enpol.2014.11.026

Elcan Industries. (n.d.). *Lithium Iron Phosphate vs Lithium Ion*. https://elcanindustries.com/toll-processing/lithium-iron-phosphate-batteries-vs-lithium-ion-batteries/#:~:text=Here%20are%20some%20key%20differences,manganese%20oxide%2C%20or%20nickel%20oxide.

Elgendy, M. (2024, February). *Exploring The Role of Manganese in Lithium-Ion Battery Technology*. https://www.azom.com/article.aspx?ArticleID=23388

Emodi, N. V., Okereke, C., Abam, F. I., Diemuodeke, O. E., Owebor, K., & Nnamani, U. A. (2022). Transport sector decarbonisation in the Global South: A systematic literature review. *Energy Strategy Reviews*, *43*, 100925. https://doi.org/10.1016/j.esr.2022.100925

ET Bureau. (2024). *India in talks with Sri Lanka to acquire graphite mine block*. https://economictimes.indiatimes.com/industry/indl-goods/svs/metals-mining/india-in-talks-with-sri-lanka-to-acquire-graphite-mine-block/articleshow/110342648.cms?from=mdr

EV Connect. (n.d.). *How Long Does an Electric Car Battery Last?* https://www.evconnect.com/blog/how-long-does-an-electric-car-battery-last

EY. (2022). *Electrifying Indian Mobility*.

Gautam, A. (2022, March). *Electric Vehicle Battery Types and its Future: EV Battery Stocks India 2022*. https://ecogears.in/types-of-electric-vehicle-batteries-and-ev-battery-stocks-in-india-2022/

Gear, L. (n.d.). *The Role and Demand for Copper in the Future Automotive Market*. https://internationalcopper.org/wp-content/uploads/2022/03/Automotive.pdf

Gerbens-Leenes, W., Hoekstra, A. Y., & van der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, *106*(25), 10219–10223. https://doi.org/10.1073/pnas.0812619106

Goonan, T. G. (2012). *Lithium Use in Batteries*. Mineral requirements for clean energy transitions – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA

ICCT. (2022). *Decarbonizing India's road transport: A meta-analysis of road transport emissions models*. https://theicct.org/publication/decarbonizing-india-road-transport-may22/

ICRA. (2023, December). *COPPER INDUSTRY*. file:///C:/Users/swetabhushan/Downloads/SH-2023-Q4-1-ICRA-Non%20Ferrous%20Metal%20Manufacturers%20(2)%20(1).pdf

IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

IEA. (2023a). *Global EV Outlook 2023—Trends in Batterieds*. vTrends in batteries – Global EV Outlook 2023 – Analysis - IEA

IEA. (2023b). *Transitioning India's Road Transport Sector*. https://www.iea.org/reports/transitioning-indias-road-transport-sector

IEA. (2024a). *Global Critical Minerals Outlook 2024*. https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

IEA. (2024b). *Global EV Data Explorer* [Dataset]. https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer

IISD. (n.d.). *The Evolution of the Clean Energy Cess on Coal Production in India*. International Institute for Sustainable Development. https://www.iisd.org/system/files/publications/stories-g20-india-en.pdf

Indian Council of Agricultural Research. (2011). *DMR Vision 2030*.

International Copper Association India Limited. (2023). *Evaluating the Electric Vehicle Battery Supply Chain and Scope of Indigenization*. https://copperindia.org/oguploads/white%20paper/Evaluating%20the%20Electric%20Vehicle%20Battery%20Supply%20Chain%20and%20Scope%20of%20Indigenization.pdf

International Council on Clean Transportation. (2021). *Battery capacity needed to power electric vehicles in India from 2020 to 2035*.

International Transport Forum. (2023a). *Life-Cycle Assessment of Passenger Transport*.

International Transport Forum. (2023b). *Life-cycle assessment of passenger transport: An Indian case study*. OECD. https://doi.org/10.1787/2d11e416-en

Jain, D., Sampat, M., Keum, S., Kumbakonam, S., & Achreja, S. (2022). *Electric Vehicles are Poised to Create a $100B+ Opportunity in India by 2030*. Bain & Company, Inc. https://www.bain.com/globalassets/noindex/2022/bain_report_electric_vehicles_are_poised_to_create_a_$100b_opportunity_in_india_by_2030.pdf

Khanna, B. (2023). *Inside India's "Deep Ocean Mission", a challenge harder than goign to space*. https://www.thehindu.com/sci-tech/science/deep-ocean-mission-matsya6000-seabed-mining-blue-economy/article67457379.ece

KNN. (2024, April). *India to Secure Copper & Cobalt Supply With New Deal With Congo*. https://knnindia.co.in/news/newsdetails/sectors/others/india-to-secure-copper-cobalt-supply-with-new-deal-with-congo#:~:text=New%20Delhi%2C%20Apr%2013%20(KNN,within%20the%20next%20three%20months.

Kumar, A. (2024, August). *India to open its 1st lithium mines in Chhattisgarh after GSI confirmation*. https://www.business-standard.com/industry/news/india-to-its-open-1st-lithium-mines-in-chhattisgarh-after-gsi-confirmation-124081401256_1.html

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

Lark, T. J., Hendricks, N. P., Smith, A., Pates, N., Spawn-Lee, S. A., Bougie, M., Booth, E. G., Kucharik, C. J., & Gibbs, H. K. (2022). Environmental outcomes of the US Renewable Fuel Standard. *Proceedings of the National Academy of Sciences*, *119*(9), e2101084119. https://doi.org/10.1073/pnas.2101084119

Lindner, J. (2024). *Cobalt Usage By Industry Statistics* [Dataset]. https://worldmetrics.org/cobalt-usage-by-industry-statistics/

Ministry of Mines. (2023, June). *Critical Minerals for India*. https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf

Ministry of Road Transport & Highways (MoRTH), Government of India. (2023, December 28). *Vahan dashboard* [Government of India]. Vahan Dashboard. https://vahan.parivahan.gov.in/vahan4dashboard/vahan/dashboardview.xhtml;jsessionid=A0FC679ED8227435213AE79A069156C9

Mittal, S., Hanaoka, T., Shukla, P. R., & Masui, T. (2015). Air pollution co-benefits of low carbon policies in road transport: A sub-national assessment for India. *Environmental Research Letters*, *10*(8), 085006. https://doi.org/10.1088/1748-9326/10/8/085006

Moors, C. (2022, August). *Battery-makers slash cobalt intensity in the face of accelerating demand*. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/battery-makers-slash-cobalt-intensity-in-the-face-of-accelerating-demand-71813202

Mulgund, S. (2024, February 13). *How LMFP batteries can power India's electric vehicle market*. https://www.ey.com/en_in/automotive-transportation/how-lmfp-batteries-can-power-india-s-electric-vehicle-market#:~:text=The%20structure%20of%20LMFP%20is,high%20amounts%20of%20power%20quickly.

Naylor, R. L., Liska, A. J., Burke, M. B., Falcon, W. P., Gaskell, J. C., Rozelle, S. D., & Cassman, K. G. (2007). The Ripple Effect: Biofuels, Food Security, and the Environment. *Environment: Science and Policy for Sustainable Development*, *49*(9), 30–43. https://doi.org/10.3200/ENVT.49.9.30-43

NewsVoir. (2024, March). *India's Copper Story Critically Dependent on the Quality of Scrap Processing*. https://www.business-standard.com/content/press-releases-ani/india-s-copper-story-critically-dependent-on-the-quality-of-scrap-processing-124031500502_1.html

NITI Aayog. (2021a). *Handbook of electric vehicle charging infrastructure implementation, Version 1*. https://www.niti.gov.in/sites/default/files/2021-08/HandbookforEVChargingInfrastructureImplementation081221.pdf

NITI Aayog. (2021b). *Roadmap for ethanol blending in India 2020-25*.

NITI Aayog. (2024). *Working Group Report on Crop Husbandry, Agriculture Inputs, Demand & Supply*. https://www.niti.gov.in/sites/default/files/2024-02/Working%20Group%20Report%20on%20Demand%20%26%20Supply%20Final_V9.pdf

OEC. (n.d.). *Copper Ore in India* [Dataset]. https://oec.world/en/profile/bilateral-product/copper-ore/reporter/ind

ORF. (2024). *Urban India's Parking Woes: An Overview*. Orfonline.Org. https://www.orfonline.org/research/urban-indias-parking-woes-an-overview

Ovrom, A. (2023). *Comparing NMC and LFP Lithium-Ion Batteries for C&I Applications*. https://www.mayfield.energy/technical-articles/comparing-nmc-and-lfp-lithium-ion-batteries-for-ci-applications/#:~:text=NMC%20batteries%20can%20achieve%201000,costs%20over%20the%20battery's%20lifespan.

Pal, D., Barun, Pradesha, Angga, & Thurlow, James. (2020). *2017/18 Social Accounting Matrix for India*. International Food Policy Research Institute.

Paladugula, A. L., Kholod, N., Chaturvedi, V., Ghosh, P. P., Pal, S., Clarke, L., Evans, M., Kyle, P., Koti, P. N., Parikh, K., Qamar, S., & Wilson, S. A. (2018). A multi-model assessment of energy and emissions for India's transportation sector through 2050. *Energy Policy*, *116*, 10–18. https://doi.org/10.1016/j.enpol.2018.01.037

Phadke, S., & Mitra, A. (2022). *STATE OF RESEARCH & DEVELOPMENT IN ELECTRIC VEHICLE BATTERY TECHNOLOGY*. https://wri-india.org/sites/default/files/State%20of%20Research%20%26%20Development%20in%20Electric%20Vehicle%20Battery%20Technology.pdf

PIB Delhi. (2021). *India to become Aatmanirbhar in Phosphatic Fertilisers*. https://pib.gov.in/PressReleasePage.aspx?PRID=1730947

PIB Delhi. (2024). *Details & Status of Critical Minerals Blocks Auction Process*. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2002706

Poupinha, C., & Dornoff, J. (2024, April). *The bigger the better? How battery size affects real-world energy consumption, cost of ownership, and life-cycle emissions of electric vehicles*. The International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2024/04/ID-80-%E2%80%93-BEVs-size-Report-A4-70138-v9.pdf

Power. (2024, April). *Improving Lithium-Ion Batteries with Silicon Anode Technology*. https://www.powermag.com/improving-lithium-ion-batteries-with-silicon-anode-technology/

PPAC. (2024). *Contribution of Petroleum Sector to Exchequer* [Online post]. https://ppac.gov.in/prices/contribution-to-central-and-state-exchequer

PTI. (2024, March). *Adani commences phase-1 operations at $1.2-billion copper plant in Mundra*. https://indianexpress.com/article/india/adani-commences-phase-1-operations-at-1-2-billion-copper-plant-in-mundra-9239107/

Reuters. (2024, April). *India seeks overseas help for lithium processing to avoid relying on China*. https://economictimes.indiatimes.com/news/economy/foreign-trade/india-seeks-overseas-help-for-lithium-processing-to-avoid-relying-on-china/articleshow/109592005.cms?from=mdr

SARKAR, H., & SUBBARAO, S. V. (1981). A Short Term Macro Forecasting Model for India—Structure and Uses. *Indian Economic Review*, *16*(1/2), 55–80.

Stanford Advanced Materials. (2023). *Cobalt in EV Batteries: Advantages, Challenges, and Alternatives*. https://www.samaterials.com/cobalt-in-ev-batteries-advantages-challenges-alternatives.html#:~:text=These%20batteries%20rely%20on%20the,density%20in%20lithium%2Dion%20batteries.

Tan, J., & Keiding, K. (2023). *The cobalt and lithium global supply chains: Status, risks and recommendations*. https://data.geus.dk/pure-pdf/MiMa-R_2023_03_web.pdf

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., & Williams, R. (2009). Beneficial Biofuels—The Food, Energy, and Environment Trilemma. *Science*, *325*(5938), 270–271. https://doi.org/10.1126/science.1177970

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A., & Flexer, V. (2023). Environmental impact of direct lithium extraction from brines. *Nature Reviews Earth & Environment*, *4*(3), Article 3. https://doi.org/10.1038/s43017-022-00387-5

West Zone Water Partnership. (2016). *Drought and Sugar Industry in Maharashtra—Are We Learning from History?* https://www.gwp.org/contentassets/4d68c9bc5baa4096907a10a6b8ead5fb/iwp_droughts-and-sugar-industry-in-maharashtra-_18july2017.pdf

World Trade Organization. (2021). *WTO | dispute settlement - DS580: India - Measures Concerning Sugar and Sugarcane*. https://docs.wto.org/dol2fe/Pages/SS/directdoc.aspx?filename=q:/WT/DS/579-10.pdf&Open=True

Zhang, R., Ma, X., & Shen, X. (2020). *Life cycle assessment of electrolytic manganese metal production*. https://www.sciencedirect.com/science/article/abs/pii/S0959652619348218#:~:text=The%20mainstream%20process%20for%20the,energy%20in%20the%20whole%20production.

8. Appendices

Appendix A. Details of studies on the social accounting matrix (SAM) in India

S. No	Reference	Salient SAM features	Suitability for energy policy analysis
1.	Sarkar & Subbarao (1981)	Base year: 1979–80 Sectors (3 in all): agriculture, industry, and services Agents: non-agricultural wage income class, non-agricultural non-wage income class, agricultural income class, and government Factors of Production: Labour and Capital	Limited suitability, due to lack of disaggregated energy/electricity sector.
2.	Sarkar & Panda (1986)	Base year: 1983–84 Sectors (6 in all): agriculture (2), industry (2), infrastructure and services Agents: non-agricultural wage income class, non-agricultural non-wage income class, agricultural income class and government Factors of Production: Labour and Capital	Limited suitability, due to lack of disaggregated energy/electricity sector
3.	Bhide & Pohit (1993)	Base year: 1985–86 Sectors (6 in all): agriculture (2); livestock & forestry; industry (2); infrastructure and services Agents: government, non-agricultural wage income earners, non-agricultural profit income earners and agricultural income earners Factors of Production: Labour and Capital	Limited suitability, due to lack of disaggregated energy/electricity sector
4.	Pradhan & Sahoo (1996)	Base year: 1989–90 Sectors (8 in all): agriculture (2), mining and quarrying, industry (2), construction, electricity combined with water and gas distribution, and services (3) Agents: government, agricultural self-employed, agricultural labour, and non-agricultural self-employed and other labour Factors of Production: Labour and Capital	Limited suitability, due to lack of disaggregated energy/electricity sector
5.	Pradhan, Sahoo, & Saluja (1999)	Base year: 1994–95 Sectors (60 in all): agriculture (4), livestock products (2), forestry sector, mining (4), manufacturing (27), machinery and equipment (6), construction, electricity, transport (2), gas and water supply, other services (11) Agents: government, self-employed in agriculture (rural & urban), self - employment in non-agriculture (rural & urban), agricultural wage earners (rural &	Limited suitability since base year needs to be updated

S. No	Reference	Salient SAM features	Suitability for energy policy analysis
		urban), other households (rural & urban), private corporate, and public non-departmental enterprises Factors of Production: Labour and Capital	
6.	Pradhan, Saluja, & Singh (2006)	Base year: 1997–98 Sectors (57 in all): agriculture (4), livestock products (2), forestry, mining, manufacturing (27), machinery and equipment (6), construction, electricity, transport (2), gas and water supply, other services (11) Agents: government, self-employed in agriculture (rural & urban), self - employment in non-agriculture (rural & urban), agricultural wage earners (rural & urban), other households (rural & urban), private corporate and public non-departmental enterprises Factors of Production: Labour and Capital	Limited suitability, since base year needs to be updated
7.	Sinha, Siddiqui, & Munjal (2007)	Base year: 1999–2000 Sectors (13 in all): agriculture (informal), formal manufacturing (9), construction (informal), other services (formal & informal) and government service Agents: rural occupation class, 4 urban occupation class, government and private corporations Factors of Production: Labour and Capital	Limited suitability, since there is no disaggregated energy/electricity sector, and because the base year needs to be updated
8.	Saluja & Yadav (2006)	Base year: 2003–04 Sectors (73 in all): agriculture (12), livestock products (4), forestry, mining (4), manufacturing (28), machinery and equipment (7), construction, energy, gas distribution, water supply, transport (2), other services (10) Agents: 5 rural households' expenditure classes, 5 urban households' expenditure classes, private corporation, public enterprises and government Factors of Production: Labour and Capital	Limited suitability, due to lack of disaggregated energy generation sector
10	Pradhan, Saluja, & Sharma (2014)	Base year: 2007–08 Sectors (85 in all): agriculture and allied sectors (22), mining (9), manufacturing (29), machinery and equipment (3), construction, electricity, water supply, transport (4), other services (18) Agents: 5 rural households' occupation classes, 4 urban households' occupation classes, private corporation, public enterprises and government Factors of Production: Labour, Capital and Land	Limited suitability, since the base year needs to be more recent
11	Pal, Pohit & Roy (2012)	Base year: 2003–04 Sectors (85 in all): agriculture and allied (21), mining (9), manufacturing (32), construction (1), electricity and water supply (5), transport (5), services (12)	Contains energy sector disaggregation but an updated version for a

S. No	Reference	Salient SAM features	Suitability for energy policy analysis
		Agents: 5 rural household classes, 4 urban household classes, private corporate, public non-departmental enterprises, government, rest of the world Factors of Production: Labour, Capital, and Land	more recent base year is required.
12	Pal, Pradesha and Thurlow (2020)	Base year: 2017–18 Sectors (112 in all): agriculture and allied (39), agriculture-based processing (18), mining (4), manufacturing other than agro-processing (24), utilities (3), construction (1), services including transport and trade (23) Agents: 5 rural farm household classes, 5 rural nonfarm household classes, 5 urban household classes, public enterprises, rest of the world, and government Factors of Production: Labour (8 types based on region and education level), 4 types of Capital, and Land	More detailed energy sector disaggregation is useful in manufacturing and utilities.

Appendix B. Critical mineral intensities of various battery chemistries accounted for in the study

NMC 811		NCA		LFP	
Minerals	Mineral intensity (kg/kWh)	Minerals	Mineral intensity (kg/ kWh)	Minerals	Mineral intensity (kg/ kWh)
Lithium	0.08	Lithium	0.1	Lithium	0.09
Nickel	0.65	Nickel	0.693	Graphite	1.05
Manganese	0.08	Cobalt	0.1325	Copper	0.7352
Cobalt	0.08	Graphite	0.733	Phosphorus	0.37
Graphite	0.75	Copper	0.755		
Copper	0.487				

Sources: Phadke & Mitra, 2022; ; IEA, 2021; Tan & Keiding, 2023; International Copper Association India Limited, 2023; Gear, n.d.

Appendix C. Comparison of annual EV numbers from SAFARI with other studies

The annual EV numbers for 2W and 3W in the CURRENT TRAJECTORY scenario are similar to the low adoption scenario from the Clean Mobility Shift Dashboard until 2027 and relatively lower going forward as shown in Figure 11 (*Clean Mobility Shift EV Dashboard*, n.d.). The annual EV numbers for 4W show very similar results to the IEA's Global EV Data Explorer until 2030, while being slightly on the higher end (IEA, 2024b). Compared with the Clean Mobility Shift Dashboard, the SAFARI results report considerably higher numbers. The number of electric buses from the SAFARI results is similar to that in the Global EV Data Explorer until 2023 and moderately dip going forward (IEA, 2024b). However, the model results are marginally higher than the results of EY's report on 'Electrifying Indian Mobility' (EY, 2022)

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