



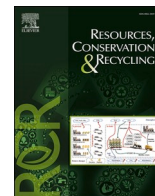
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Full length article

Saturation-aware critical raw material demands of India's multi-modal passenger EV transition

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ABSTRACT

Critical raw material (CRM) availability is a key constraint for large-scale transport electrification in emerging economies. To assess India's transition, lithium, cobalt, nickel, manganese, and copper demand from 2022 to 2050 is analysed using a saturation-aware dynamic material flow model with mode-specific saturation limits across five passenger modes and IEA-aligned scenarios (STEPS, APS, EV30@30). India's multi-modal structure produces a dual-rate electrification pathway distinct from the car-centric systems in developed markets. Two-wheelers and auto-rickshaws electrify early, and net stock tapers as they approach saturation, limiting long-term CRM contribution, while electric cars expand through 2050 and dominate battery and CRM demand. Despite the gradual shift from fleet expansion to replacement, CRM demand rises sharply: by 2050, lithium and copper exceed 2022's global production levels, cobalt and nickel approach or exceed, and manganese remains lower. These findings highlight India's growing influence on global CRM markets and the need for coordinated national strategies.

1. Introduction

The global transition toward electric vehicles (EVs) is central to reducing greenhouse gas emissions and fossil-fuel dependence. However, electrification also places growing pressure on critical raw materials (CRMs) such as lithium, cobalt, nickel, and copper, which are essential for batteries, vehicle components, and charging infrastructure (Habib et al., 2020; Hache et al., 2019; Jones et al., 2020). CRM availability is increasingly recognised as a key constraint for large-scale transport electrification, and international scenario frameworks, including the Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and EV30@30 campaign under the Electric Vehicle Initiative, provide different trajectories for EV deployment (IEA, 2019, 2023). Comparing these frameworks helps assess how infrastructure, technology, and supply chains must evolve to support this transition while addressing long-term resource sustainability (Dhar et al., 2017). India is important in this context: its population exceeds 1.4 billion, and its vehicle fleet tripled to 326 million by 2020 (MoRTH, 2020). Its transport sector contributes 14% of national CO₂ emissions (Kumar et al., 2022), relies heavily on imported fossil fuels (75% in 2019) (IEA,

2021), and drives severe urban air pollution (NRDC, 2019). Unlike car-centric transitions in developed economies, India's mobility system is strongly multi-modal and dominated by two-wheelers and auto-rickshaws, making its electrification pathway distinct and central to supporting India's commitments under the Paris Agreement (UNFCCC, 2015) on both emission reduction and CRM sustainability.

While EV adoption can reduce operational emissions, CRM demand in emerging economies remains insufficiently studied (Abdul-Manan et al., 2022; Das et al., 2021; Milovanoff et al., 2020; Verma et al., 2022; Watari et al., 2019a, 2019b). Global CRM assessments (Habib et al., 2020; Hache et al., 2019; Jones et al., 2020) do not capture the material implications of India's structurally diverse transport system, and national studies often focus on single modes or developed countries (de la Torre Palacios et al., 2021; Milovanoff et al., 2020). Recent studies in dynamic material flow analysis and related approaches assess lithium-ion battery metal demand, recycling potential and circular strategies in high-income or predominantly car-based systems (Dunn et al., 2022; Kamran et al., 2021; Maisel et al., 2023; Raghavan et al., 2023; Rosenberg et al., 2023; Takimoto et al., 2024). Existing research on chargers (Goel et al., 2021; Habib et al., 2020; Hao et al., 2019;

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Majumdar et al., 2015), battery materials (Watari et al., 2019b), and energy impacts (Taljegard et al., 2019) does not integrate CRM requirements across vehicles, chargers, and batteries, nor does it account for mode-specific saturation effects that shape long-term evolution. Our study complements this literature by applying a saturation-aware DMFA to India's multi-modal passenger system, jointly modelling EV stocks, chargers, and batteries across five modes under policy-driven scenarios and comparing the resulting CRM requirements with current global production benchmarks. Although national policy initiatives such as

Faster Adoption and Manufacturing of Electric Vehicles (FAME) and the National Electric Mobility Mission Plan (NEMMP), supported by multiple regional EV policies (Table S1 in Supplementary Information 1 (SI-I)) (E-AMRIT, 2023; MoHI, 2022; MoP, 2022; NEMMP, 2020), encourage faster adoption, they do not evaluate long-term resource pressures or CRM supply constraints. As a result, an assessment that links EV growth, charging needs, battery demand, and CRM requirements across India's future electrification pathways remains missing.

To address this gap, this study applies a Dynamic Material Flow

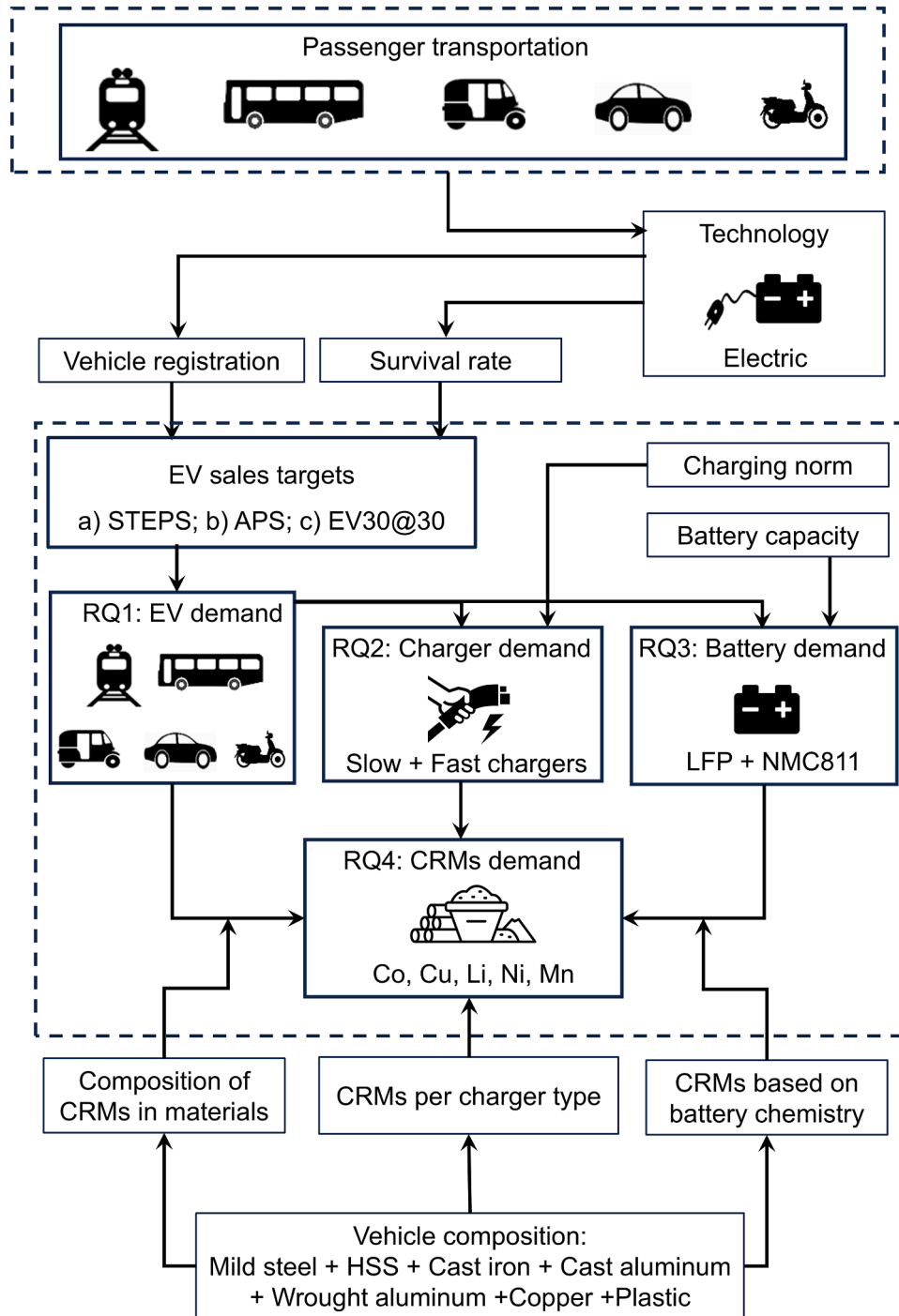


Fig. 1. Schematic of the Dynamic Material Flow Analysis Model for electric vehicle transition in Indian passenger transportation. Icons are created by 'Luis Prado' and 'Mira iconic' from the noun project. Here, HSS: High Strength Steel; ICE: Internal Combustion Engine; STEPS: Stated Policies Scenario; APS: Announced Pledges Scenario; EV30@30: campaign under Electric Vehicle Initiative; LFP: Lithium Iron Phosphate; NMC811: Nickel Manganese Cobalt Oxide (80% Nickel, 10% Manganese, 10% Cobalt); Co: Cobalt; Cu: Copper; Li: Lithium; Ni: Nickel; Mn: Manganese.

Analysis (DMFA), which captures stock–flow dynamics, temporal changes, and mode-specific saturation limits. Compared with static MFA or econometric models (Jones et al., 2020; Lipman and Maier, 2021; TandE, 2017; Tintelean et al., 2020), DMFA is better suited to India's rapidly changing EV landscape. The analysis evaluates India's passenger transport electrification from 2022 to 2050 under STEPS, APS, and EV30@30 across five major modes: trains, buses, auto-rickshaws, cars, and two-wheelers. It answers four research questions: RQ1: How would India's EV stock evolve under the three scenarios? RQ2: What is the associated charging infrastructure? RQ3: What is the associated battery demand? RQ4: What is the associated CRM demand for EVs, chargers, and batteries? The findings can offer insight into how India's structurally diverse EV transition shapes long-term CRM requirements and how adoption patterns may influence infrastructure planning. The results provide evidence on the scale of India's material demand during large-scale electrification and underscore the importance of CRM-focused planning for transport transitions in emerging economies. These insights are also relevant for other populous emerging economies with comparable mobility structures. The following section details the development of the model, data, and assumptions; Sections 3 and 4 present the findings and discuss their implications; and the final section concludes the study.

2. Model development and data

2.1. Focus and scope

The study models the electrification of five passenger transportation modes in India (Fig. 1): trains, buses, auto-rickshaws, cars, and two-wheelers. Other passenger modes with limited electrification potential or minimal CRM relevance are excluded. This selection aligns with national EV policies such as FAME and NEMMP (Das et al., 2021; MoHI, 2022; NEMMP, 2020). The base year is 2022 due to data availability, 2030 represents India's short-term Nationally Determined Contributions (NDC) commitments, and 2050 represents the horizon year to evaluate long-term trends (Das et al., 2021; IEA, 2019, 2023; UNFCCC, 2016).

2.2. Passenger transportation data

Historical vehicle registration data were obtained from Indian Railways (2020b, 2020a) and MoSPI (2017). Vehicle ownership trends were projected using the Gompertz model (Singh et al., 2020), which captures S-shaped growth and saturation dynamics. Estimation of the model parameters allows projection of ownership levels and expected saturation timing:

$$V_{m,t}^* = \gamma e^{\alpha_m} e^{\beta_m GDP_t} \quad (1)$$

Linearizing by taking the natural logarithm twice:

$$\ln(\ln(V_{m,t}^*)) = \ln(\ln(\gamma)) + \ln(\alpha_m) + \beta_m GDP_t \quad (2)$$

There is no standard method to estimate saturation levels. While some studies use the S-curve growth function, most rely on rules of thumb, such as one car per family or per capita vehicle ownership (Das, 2010). In this study, saturation levels are based on existing literature on India that considers the average number of cars per household, the seating capacities of auto rickshaws, and historical vehicle ownership rates relative to GDP per capita in other Asian countries for two-wheelers (Das, 2010; Singh et al., 2020). Therefore, $V_{m,t}^*$ is projected vehicle ownership per 1000 people at time 't' for mode 'm'. ' γ ' is the saturation level (200 for cars, 300 for two-wheelers, and 120 for auto-rickshaws) (Das, 2010; Singh et al., 2020). Mass public transportation is running at capacity, so no saturation is assumed for trains and buses. ' α_m ' and ' β_m ' are shape parameters estimated from historical data. ' GDP_t ' is India's Gross Domestic Product (IMF, 2019; MoEFCC, 2023).

2.3. Vehicle obsolescence

Annual vehicle obsolescence is estimated using a logistic survival function (Eq. (3)) (Pandey and Venkataraman, 2014; Yan et al., 2011). This function, ' $O_{t,m}$ ', evaluates vehicle survival rates based on shape factor ' δ_m ' and median retirement age ' $R_{50,m}$ ' (Lakshmi et al., 2014; Pandey and Venkataraman, 2014).

$$O_{t,m} = \frac{1}{1 + e^{\left\{ \delta_m \left(1 - \frac{t}{R_{50,m}} \right) \right\}}} \quad (3)$$

Cumulative obsolescence, tracked up to the horizon year, is represented by ' $O_{t,m}^{cum}$ ' (Eq. (4)),

$$O_{t,m}^{cum} = \sum_y^t Y_y \times O_{t-y,m} \quad (4)$$

2.4. Electrification growth

This study assesses EV growth in India using STEPS, APS, and EV30@30 pathways, characterized by their specific 2030 EV sales targets (refer to Table S2 in SI-I). A two-step approach is employed to estimate EV stock and sales by 2050. First, EV sales are projected up to 2030 based on the respective sales targets for each pathway. Then, these projections are further extended to 2050 by assuming that the projected growth rate in yearly sales ' G_m ' matches the year-on-year increase observed between 2029 and 2030:

$$Y_{t,m} = Y_{t-1,m} \times (1 + G_m) \quad (5)$$

Cumulative EV stock ' $S_{t,m}$ ' is calculated as:

$$S_{t,m} = S_{t-1,m} + Y_{t,m} - O_{t,m}^{cum} \quad (6)$$

2.5. Charging infrastructure

Charging infrastructure to support EVs distinguishes between slow chargers (SC) and fast chargers (FC). Annual additions of individual SC and FC sockets in year t are estimated using Eqs. (7) and 8:

$$SC_t = \sum_m \frac{Y_{t,m}}{N_{SC,m}} \quad (7)$$

$$FC_t = \sum_m \frac{Y_{t,m}}{N_{FC,m}} \quad (8)$$

Here, SC_t and FC_t denote the number of new SC and FC sockets required in year t . ' $N_{SC,m}$ ' and ' $N_{FC,m}$ ' represent time-varying national-scale provisioning ratios (EVs per public charger) for each mode, based on the national-scale provisioning ratios developed in this study (see SI-I Section 2.5 for detailed methodology and year-wise values). These ratios are calibrated using international EV-per-public-charger benchmarks and India-specific usage patterns, so utilisation and charging behaviour are reflected through the gradual increase in EVs per charger as the system matures.

2.6. Battery demand

Battery demand is estimated using a database on battery capacities in current models in India (Table S8 in SI-I) (Gode et al., 2021). Assuming each battery lasts the entire vehicle lifespan aligns with trends in battery longevity (Sagarika et al., 2021). It also anticipates improvements in vehicle efficiency (Berjoza and Jurgena, 2017; Das et al., 2022a; Duan et al., 2018; Shiau et al., 2009), incorporating improved vehicle efficiency in km/kWh till 2050 (Das et al., 2022a). Annual new battery demand ' $B_{d,m}$ ' is calculated by Eq. (9). Here, ' $Y_{t,m}$ ' is EV sales and ' $B_{t,m}$ ' is the battery capacity for each mode.

$$B_{d,m} = \sum_m (Y_{t,m} \times B_{i,m}) \quad (9)$$

2.7. CRMs for EVs

Metals essential for EV manufacturing, include cobalt, copper, lithium, nickel, and manganese (Chadha and Sivamani, 2021; Gallo et al., 2022; International Copper Association, 2017; Knehr et al., 2022), all except manganese included in India's CRM list (Ministry of Mines, 2023). Nonetheless, given that the CRM lists from the United States (US), the European Union (EU), and Australia (Australian Government, 2023; European Commission, 2023; Hendrix, 2023; U.S. Geological Survey, 2022) include manganese and India's import reliance (Chadha and Sivamani, 2021; Ministry of Mines, 2023), it is included in the assessment (Table S9 in SI-I). They together constitute the five CRMs analysed in this study.

The study quantifies CRM demand in EVs, chargers, and batteries. CRM demand in EVs (excluding batteries) is estimated by calculating standard material weights for each EV type, distributing them among primary materials (mild steel, high-strength steel, cast iron, cast aluminium, wrought aluminium, and copper) (Das et al., 2022a, 2022b). Aggregated CRMs are identified in parts per million (ppm) for these materials (Løvik et al., 2021). The total annual CRM demand for EV components (excluding batteries) is calculated using Eq. (10). Here, 'Mat_Sh_{mat}' denotes the share of material "mat" in each vehicle type "m", and c represents the specific CRM (lithium, cobalt, nickel, manganese, or copper).

$$Q_{t,c}^{CRM, Veh, Tot} = \sum_m Q_{t,m,c}^{CRM, Veh} = \sum_m \sum_{mat} (Y_{t,m}) \times Mat_Sh_{mat,m} \times CRM_{mat,c,ppm}. \quad (10)$$

For chargers, CRM content for each SC and FC is sourced from literature (International Copper Association, 2017). The total CRM requirements for chargers in year 't' is calculated using Eq. (11).

$$Q_{t,c}^{CRM, Char, Tot} = \sum_c (SC_t \times CRM_{SC,c,kg}) + (FC_t \times CRM_{FC,c,kg}) \quad (11)$$

Battery CRM demand is based on current technologies and energy density values (Knehr et al., 2022). Lithium iron phosphate (LFP) batteries are chosen for buses, auto-rickshaws, and two-wheelers (Walvekar et al., 2022; Yang et al., 2021), while Nickel Manganese Cobalt 8:1:1 (NMC811) batteries are used for cars (Dunn et al., 2021; Xiong et al., 2019) (Table S10 and S11 in SI-I). The total CRM demand for batteries is calculated by Eq. (12).

$$Q_{t,c}^{CRM, Bat, Tot} = \sum_m \sum_c Q_{t,m,c}^{CRM, Bat} = \sum_m \sum_c B_{d,m} \times CRM_{Bat,m,c,kg/kWh} \quad (12)$$

CRM demand aggregates each CRM's demand across EV components, chargers, and batteries using Eq. (13).

$$Q_{t,c}^{CRM, Tot} = Q_{t,c}^{CRM, Veh, Tot} + Q_{t,c}^{CRM, Char, Tot} + Q_{t,c}^{CRM, Bat, Tot} \quad (13)$$

2.8. Methodological consideration

In addition to comparing STEPS, APS, and EV30@30, we assess robustness of CRM outcomes using a structured sensitivity analysis around the APS pathway. APS is used as the baseline because it represents a policy-delivery case in which all announced climate and energy targets are implemented in full and on time, providing a policy-relevant central reference scenario. The study applies (i) a multi-factor sensitivity in which key uncertain assumptions are varied jointly to represent conservative and progressive futures and (ii) one-factor-at-a-time (OFAT) tests in which each assumption is varied individually while others are held at baseline. The parameters tested include mode-specific saturation ceilings, battery chemistry shares, copper intensity per charger, batteries per vehicle over lifetime (replacement/extended life),

post-2030 sales growth extrapolation, and secondary supply share (recycling). Baseline results should be interpreted as conditional outcomes under a continuation parameterisation; sensitivity cases provide bounded deviations around this baseline (numeric outputs in SI-II). The assumed secondary supply share represents a system-level net-primary adjustment and may include recycled material from other domestic scrap streams (Cu, Ni, Mn) and international EV recycling markets (Li, Co), rather than solely Indian EV end-of-life flows. The sensitivity design and parameter ranges are documented in SI-I Section 2.8, and the results are summarised in Fig. 6.

3. Results

3.1. Electric vehicle demand

To address RQ1, India's passenger EV market evolution across all modes under the three scenarios is examined (Fig. 2). Growth slows as each mode approaches its ownership saturation ceiling. New train additions are already fully electrified in 2022, and the electric train fleet reaches 58% in 2030 (10,860 units), continuing to increase gradually toward near-complete stock electrification by 2050. This slower stock turnover occurs because trains remain in service for several decades. Electric-bus sales grow from 4900 units in 2022 to 40,000–50,000 units in 2030, representing 20–25% of registrations, and increase by a further factor of about three between 2030 and 2050. No saturation ceiling is imposed for buses, as fleet size is determined by service requirements rather than ownership patterns. The electric auto-rickshaw segment, with a fleet share of around 30% in 2022, increases to 50–60% by 2030. Under EV30@30 scenario, electric auto-rickshaw sales reach 100% by mid 2040s, and fleet stock increases from 8–10 million units in 2030 to around 160 million units by 2050, depending on scenario. Consistent with the ownership ceiling of 120 vehicles per 1000 people, net stock growth begins to taper from the late-2030s onward as the fleet moves toward saturation, even while electric sales remain high due to ongoing replacement demand. Electric car sales reach 1–1.5 million units by 2030, and by 2050, the segment grows nearly an order of magnitude or more from 2030 levels. The modeled saturation level of 200 cars per 1000 people is not reached in any scenario, and the electric-car stock continues expanding through 2050. The electric two-wheeler segment grows from 0.8 million units in 2022 to a 50–72% market share by 2030. Under all scenarios, two-wheeler electrification reaches 100% of sales between the mid-2030s and early-2040s. With a saturation level of 300 vehicles per 1000 people, this segment is the first to visibly taper: net stock growth slows from the mid-2030s as ownership approaches saturation, while electric sales remain substantial primarily because of replacement demand. Across all modes, ownership saturation acts as a structural constraint on long-run stock growth. Differences between scenarios narrow over time, with APS and EV30@30 showing higher early growth than STEPS but converging toward more similar stock levels by 2050 because of saturation tapering in the two- and three-wheeler segments. By 2050, auto-rickshaws and two-wheelers approach their saturation ceilings, while cars, buses, and trains remain below modeled thresholds. These saturation levels determine the long-term size of each fleet and directly influence the associated demand for chargers, batteries, and CRM.

3.2. Charger and battery demand

To address RQ2 and RQ3, Fig. 3 presents the growth of SCs, FCs, and battery demand across modes and scenarios. In 2022, SC demand is dominated by electric auto-rickshaws, accounting for 56% of all SCs. As two-wheelers and cars increase their EV shares, these modes account for most SC growth over time. By 2030, total SC demand increases by 6–9 times compared to 2022, with two-wheelers and auto-rickshaws making up to 87% of all SCs. By 2050, two-wheelers account for 36–50% of SC demand, with auto-rickshaws and cars making up most of the

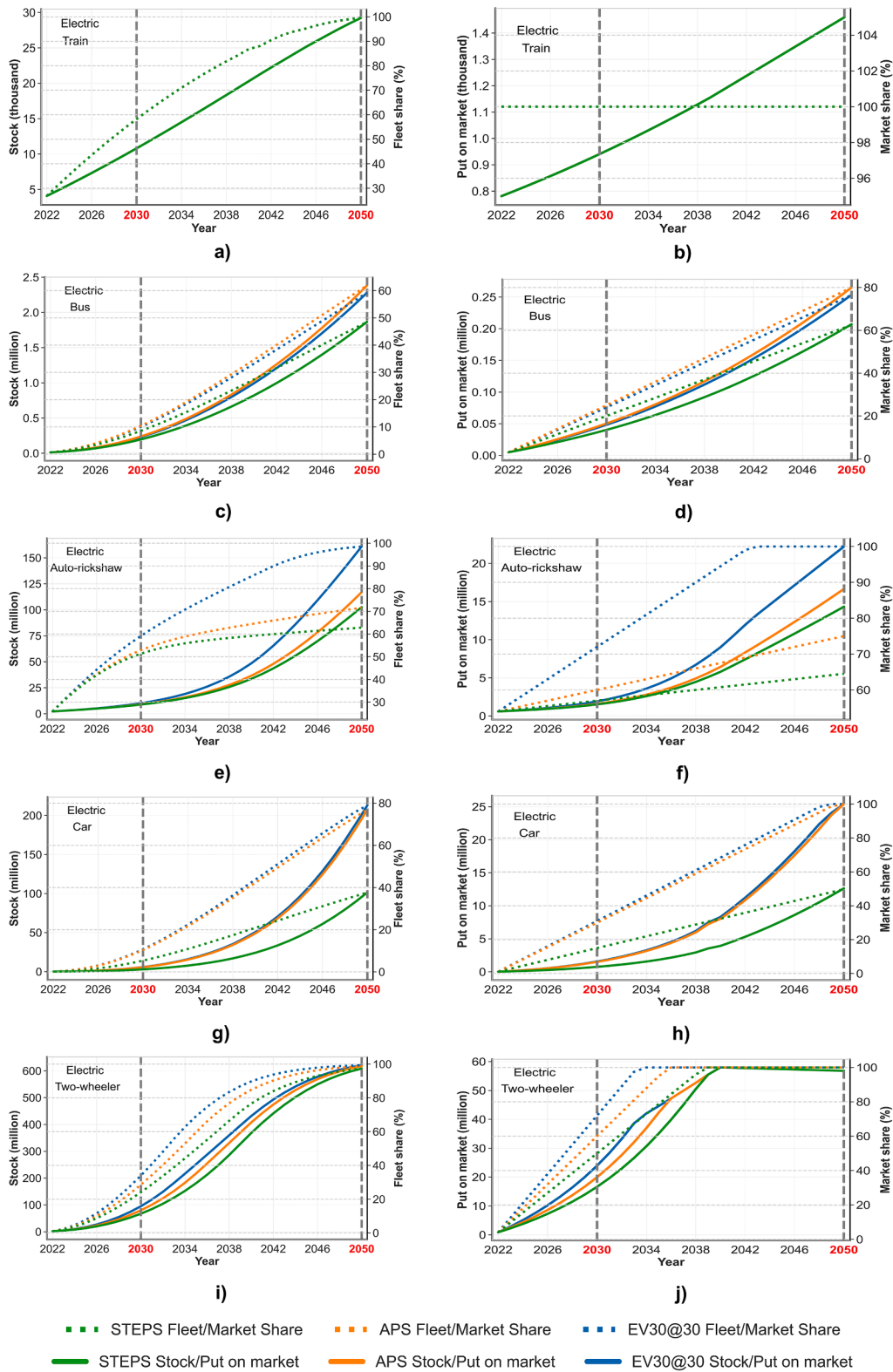


Fig. 2. Projected EV adoption in India (2022–2050) across passenger transport modes under three scenarios: STEPS (green), APS (orange), and EV30@30 (blue). Panels a), c), e), g), and i) show EV stock and fleet share; b), d), f), h), and j) show annual EV sales (“put on market”) and market share for trains, buses, auto-rickshaws, cars, and two-wheelers. Solid lines indicate absolute numbers (left axis), dotted lines show percentage shares (right axis).

remainder. FC demand is low in 2022, with around 1700 units, mainly for buses. By 2030, FC demand increases to 18,000–30,000 units, and by 2050 rises further by a factor of about five or more. Electric cars account for 80–86% of FC demand by 2050, reflecting their higher fast-charging

requirements relative to other modes.

Battery demand increases across all modes. By 2030, electric cars contribute 30–42% of total new battery demand, while two-wheelers contribute 45–54%. By 2050, electric cars account increases to

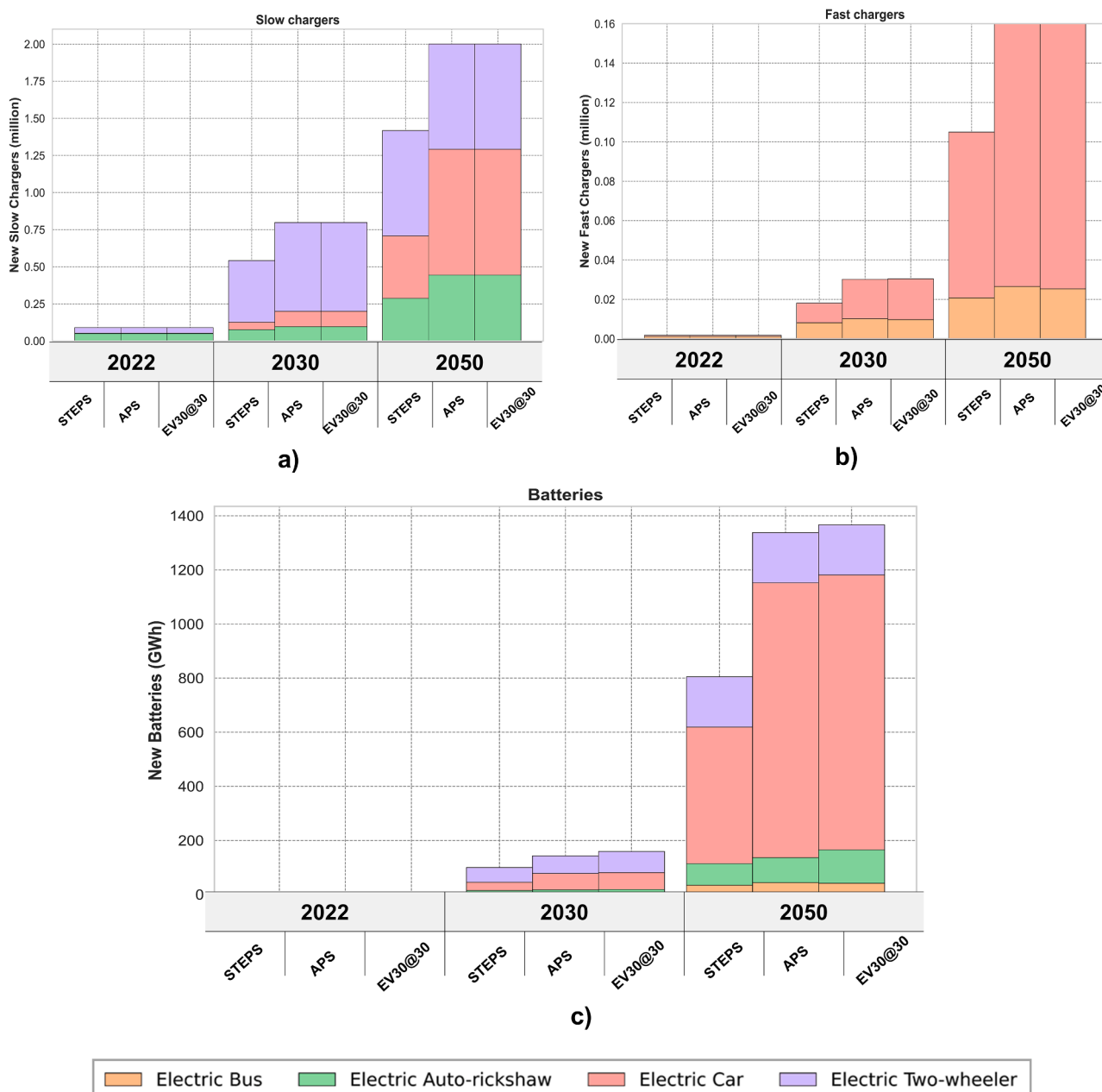


Fig. 3. Evolution of charging infrastructure and battery demand for the electrification of passenger transportation in India from 2022 to 2050 across three scenarios: STEPS, APS, and EV30@30. Panel (a) shows the growth in the number of slow chargers (in million), while panel (b) displays the trajectory for fast chargers (in million), both categorized by vehicle type, including Electric Bus, Electric Auto-rickshaw, Electric Car, and Electric Two-wheeler. Panel (c) shows the projected demand for new batteries (in GWh) required by these EV types under the same scenarios. Here, STEPS: Stated Policies Scenario; APS: Announced Pledges Scenario; and EV30@30: campaign under Electric Vehicle Initiative.

62–74% of total battery demand, with two-wheelers contributing the next largest share. Across all years, the EV30@30 scenario produces the highest charger and battery demand, followed by APS and then STEPS.

3.3. CRM demand

To address RQ4, CRM demand is quantified across all materials and scenarios (Fig. 4). Cobalt demand rises from 79 tonnes in 2022 to more than 50 times higher by 2050 under STEPS and to nearly double that level under APS and EV30@30. This increase is driven by the growing battery demand in cars using NMC batteries. Copper demand for EVs (excluding batteries) increases by 40–60 times by 2050 compared to 2022. Copper demand in batteries increases by 60–90 times, and copper

used in chargers grows by 24–39 times. Copper demand rises due to the expansion of EV stock, larger battery capacities, and higher charger deployment. Lithium demand grows around 100 times by 2050 under STEPS and almost doubles under EV30@30, reflecting the increase in total battery capacity installed each year. Nickel demand increases from slightly over 650 tonnes in 2022 to more than 16 times the 2030 level of 20–41 thousand tonnes by 2050 in all scenarios. This growth is determined by the rise in long-range EVs requiring higher nickel content per kWh. Manganese demand increases 45-fold by 2050 under STEPS, and battery-related manganese demand grows from around 79 tonnes in 2022 to nearly 20 times the 2030 level by 2050. Under APS and EV30@30, manganese demand is almost twice that of STEPS. Across all CRMs, scenario differences widen after 2030, with EV30@30 showing

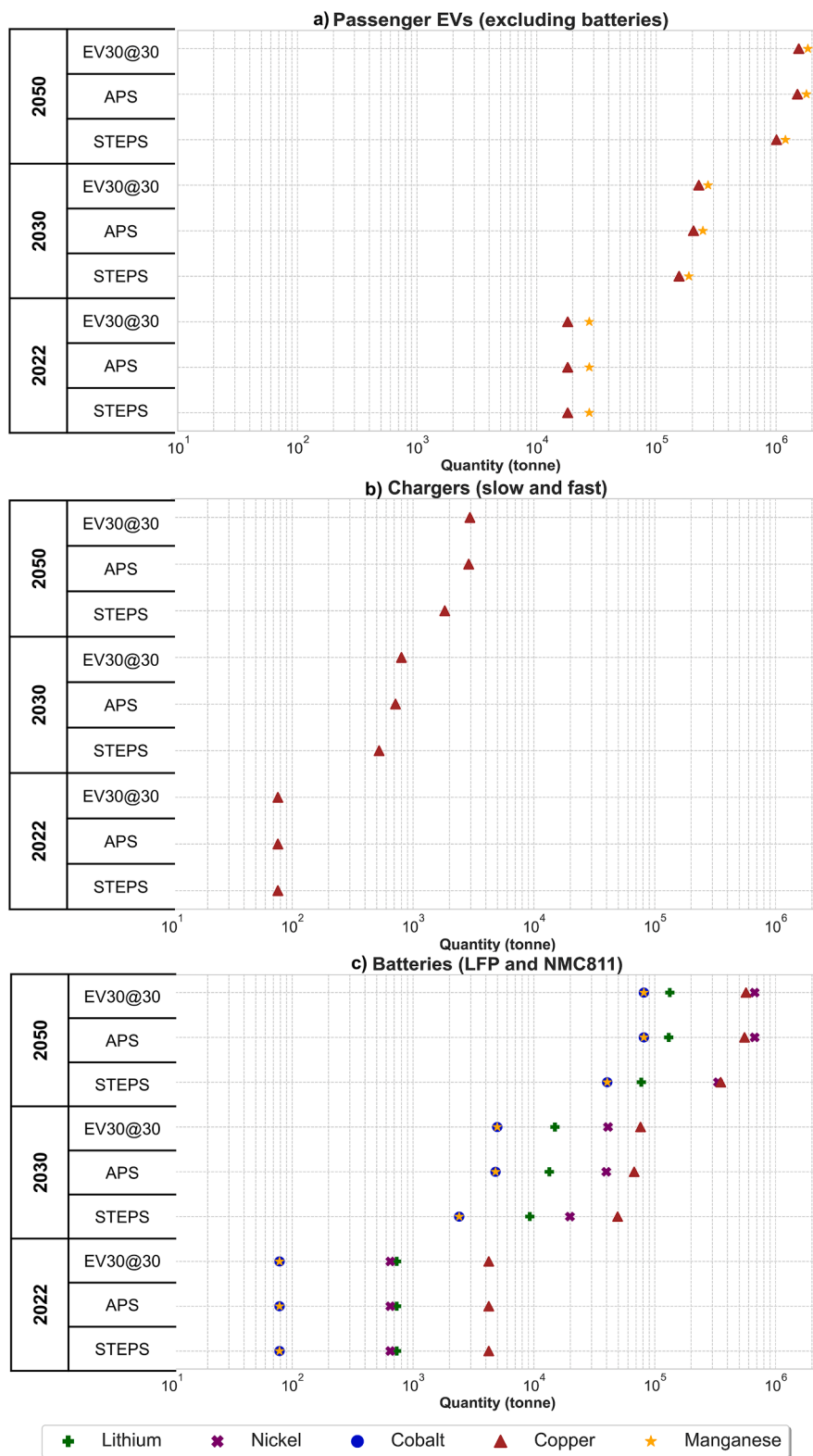


Fig. 4. Projected demand for the five critical raw materials (CRMs) assessed in this study under STEPS, APS, and EV30@30 scenarios for 2022, 2030, and 2050. Panels show metals in EVs (top), chargers (middle), and batteries (bottom): cobalt (blue), copper (brown), lithium (green), nickel (purple), and manganese (orange). Here, STEPS: Stated Policies Scenario; APS: Announced Pledges Scenario; and EV30@30: campaign under Electric Vehicle Initiative.

the highest material requirements, followed by APS and then STEPS.

3.4. Comparison with global demand

Extending RQ4, India's projected CRM and EV-related demands are compared with 2022 global production levels (Fig. 5). The results show

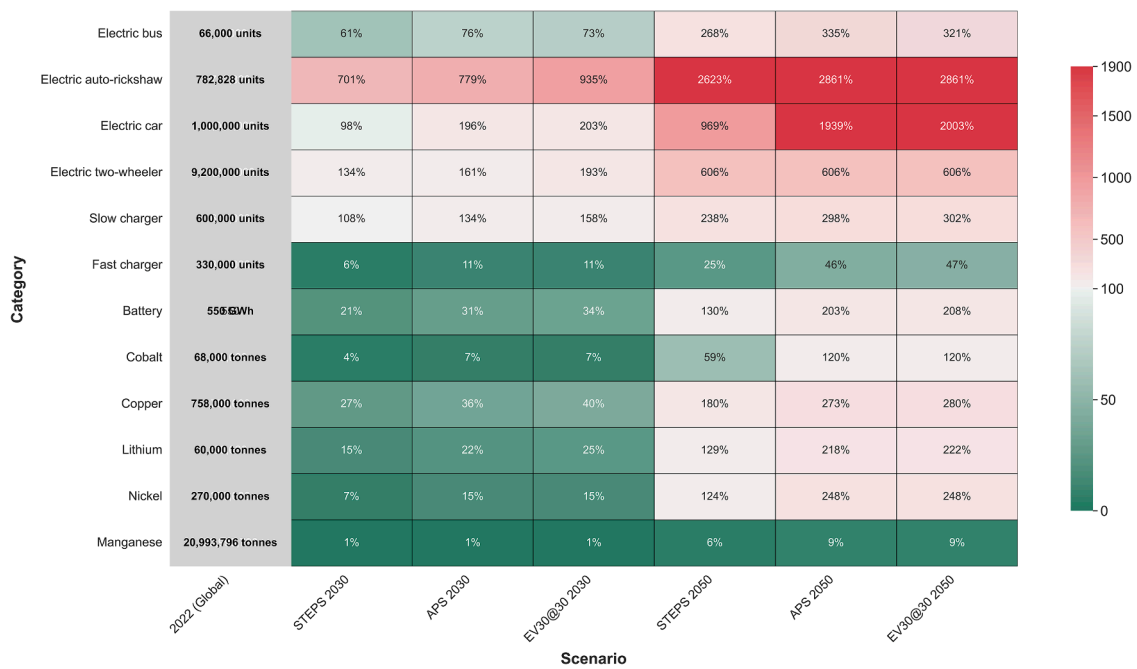


Fig. 5. This figure presents a heatmap comparison of India's STEPS, APS, and EV30@30 for projections in 2030 and 2050 with global 2022 level. The categories included in this comparison include different types of passenger transportation EVs (electric buses, auto-rickshaws, cars, and two-wheelers), chargers (slow and fast), battery capacity, and critical raw materials (CRMs) such as cobalt, copper, lithium, nickel, and manganese. The 2022 global production values for the selected CRMs are from (USGS, 2022). These 2022 values serve as a fixed reference baseline and do not represent assumed future production levels. The Y-axis lists these categories, while the X-axis represents different scenarios, with 2022 (Global) as the baseline, showing absolute global values from that year. The color coding reflects the percentage of 2022 global levels India is to achieve, with green indicating lower percentages (below the baseline) and red indicating higher percentages (exceeding the baseline). The percentages in each cell show how much of the 2022 global benchmark India reaches. **Note:** This comparison does not include electric trains due to a lack of global data. Here, STEPS: Stated Policies Scenario; APS: Announced Pledges Scenario; and EV30@30: campaign under Electric Vehicle Initiative.

that several EV categories in India reach substantial shares of global CRM use by 2030 and 2050. Electric auto-rickshaws reach up to 26–28 times the 2022 global reference level by 2050, reflecting their large projected stock. Electric cars reach around 20 times the global reference level. Electric buses increase to around 3 times, and electric two-wheelers reach around six times the 2022 global level. For charging infrastructure, slow chargers reach up to 3 times the 2022 global benchmark by 2050 under EV30@30. Fast chargers remain below the global benchmark, reaching around 50% of the 2022 global level. Battery demand reaches about twice the 2022 global reference level by 2050 in all scenarios. CRM requirements also rise relative to global benchmarks. Lithium, copper, and nickel demand each reach around double the 2022 global level by 2050. Cobalt demand approaches the same level as the 2022 global benchmark, while manganese demand remains below 10% of the global reference. The comparison illustrates the scale of India's prospective demand relative to today's supply. Future growth in global mining and refining capacity would reduce India's percentage shares relative to actual 2050 output, but the projected order of magnitude still signals that India could become a major demand centre for these CRMs.

3.5. Sensitivity analysis

The sensitivity analysis confirms that the qualitative conclusions are robust: by 2050, lithium, copper, and nickel remain the dominant pressure points on future global supply, while manganese remains comparatively low. In the multi-factor cases, conservative assumptions increase 2050 demand substantially across cobalt, lithium, and nickel, whereas progressive assumptions reduce primary demand strongly, particularly for cobalt and nickel. OFAT results show that saturation ceilings and battery lifetime/replacement assumptions are among the strongest drivers of 2050 outcomes, while battery chemistry primarily affects cobalt and nickel, and charger copper intensity has a minor effect

at the system level. Full parameter definitions and results are provided in SI-I Section 2.8 and Fig. 6.

4. Discussions

4.1. Electric vehicle demand

India's EV demand trajectory reflects the combined influence of its multi-modal mobility structure, saturation dynamics, and variation across electrification pathways. Two-wheelers and auto-rickshaws dominate India's passenger fleet today (MoRTH, 2020), and therefore, electrify the earliest. This mirrors patterns in Southeast Asian markets, where underlying affordability constraints and short-range travel patterns drive the adoption of small vehicles in early EV diffusion (Gupta et al., 2023; TERI, 2019). In our results, these two modes move toward their ownership saturation ceilings relatively early, with net stock growth tapering as the ceilings are approached, leading to rapid early growth followed by a slowdown once fleet turnover becomes the primary source of new EV additions. This shift from expansion to replacement illustrates how saturation operates as a structural constraint rather than simply an upper bound. The findings, therefore, highlight the importance of using saturation-aware stock-flow modelling for countries with heterogeneous fleets; diffusion-only approaches may overestimate long-term EV uptake if structural limits are ignored, as shown in previous material stock assessments (Jones et al., 2020; Watari, McLellan, et al., 2019). These dynamics contrast sharply with EV pathways in car-centric markets such as the US and the EU, where modelling studies typically assume continuous increases in car ownership and do not impose mode-specific saturation limits (Ghandi and Paltsev, 2020; Milovanoff et al., 2020). In those regions, long-term EV adoption primarily reflects technology diffusion within a single dominant mode (light-duty vehicles). In India, early saturation in small vehicles and continued growth in cars produce a dual-rate transition that

Sensitivity analysis: multi-factor cases (top) and OFAT ranges at 2050 (bottom)

Values are expressed as % of global 2022 production (global 2022 = 100%)

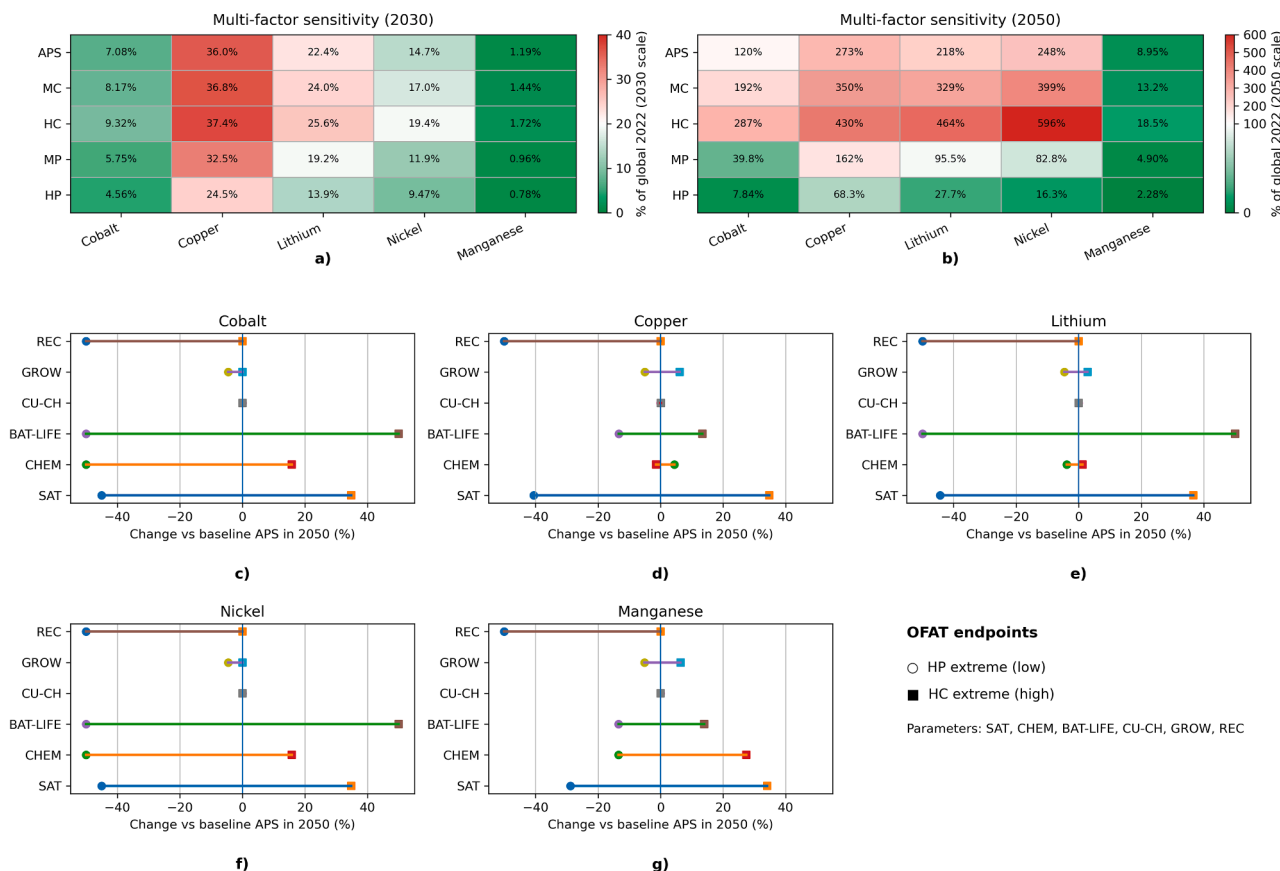


Fig. 6. Sensitivity analysis summary for India’s CRM demand (relative to global 2022 production; global 2022 = 100%). Panels a-b show multi-factor sensitivity results under the APS baseline, where key assumptions are varied jointly to form four internally consistent cases: MC (moderately conservative) and HC (highly conservative), representing higher primary material pressure and weaker circular economy progress; and MP (moderately progressive) and HP (highly progressive), representing stronger innovation and circularity. Values in each cell report India’s annual demand for each CRM expressed as a percentage of global 2022 production in the corresponding year. Panel a reports 2030 outcomes; panel b reports 2050 outcomes. Green indicates lower values and red indicates higher values within the panel-specific scales. Panels c–g show one-factor-at-a-time (OFAT) sensitivity at 2050, expressed as percentage change relative to the APS baseline for each CRM. In each OFAT test, one assumption is varied to a high extreme (HC extreme) or low extreme (HP extreme) while all other assumptions remain at baseline. The plotted range, therefore, represents the effect of that single assumption on 2050 demand. The tested parameters are SAT (saturation ceilings), CHEM (battery chemistry shares), BAT-LIFE (batteries per vehicle over lifetime), CU-CH (copper content per charger), GROW (post-2030 sales growth), and REC (secondary supply share). Endpoint markers denote the low (HP) and high (HC) extremes. Definitions and parameter ranges for MC/HC/MP/HP and for OFAT extremes are provided in SI-I Section 2.8. The underlying numeric values are provided in SI-II (Excel), sheets “Figure 6(a,b)” and “Figure 6(c-g)”.

differs fundamentally from car-based systems.

Electric cars, by contrast, remain far from saturation even by 2050 (Srivastava et al., 2022). Consequently, they become the strongest long-term driver of growth in batteries and CRMs, as they require larger, higher-energy-density batteries with greater nickel, lithium, and copper intensities (Dunn et al., 2021; Xu et al., 2020). Similar global assessments show that long-range cars dominate cumulative CRM demand even when they form a smaller share of total EVs (Habib et al., 2020; Hache et al., 2019). For India, this indicates that while early electrification is carried by two- and three-wheelers, the long-term material demand depends increasingly on car adoption trajectories. Buses and trains show a different pattern due to long lifetimes and public-sector ownership. Even when sales become fully electric, stock electrification proceeds slowly because retirement cycles span decades. This lag is consistent with observations from large public fleets in China and Europe (IEA, 2024). Their trajectory, therefore, reflects procurement and infrastructure planning rather than consumer adoption, indicating that public-fleet electrification depends on coordinated long-term investment.

These results have three implications for India. First, early tapering

toward saturation of two-wheelers and auto-rickshaws limits long-term uncertainty in these modes, shifting scenario divergence toward cars, where sales differences remain substantial by 2050. Second, because car batteries dominate CRM requirements globally (Milovanoff et al., 2020; Xu et al., 2020), India’s future material demand is sensitive to car uptake, even if smaller vehicles electrify more quickly. Third, India’s structurally diverse system means that electrification trajectories differ fundamentally from those in the EU or US, and applying car-centric projections would misrepresent long-term resource and infrastructure needs. Fourth, a key implication of these findings is that even when sales reach full electrification, fleet transitions continue slowly because legacy ICE vehicles remain in operation for extended periods. This phenomenon is also documented in the EU and North America, where EV adoption outpaces stock turnover (Cazzola et al., 2023; IEA, 2024; Roca-Puigròs et al., 2023). For India, this dual system means that long-term planning must accommodate both an expanding EV fleet and a diminishing but persistent conventional fleet. Finally, the findings underscore a methodological point: dynamic stock–flow analysis with explicit saturation constraints captures India’s fleet evolution more accurately than models based solely on sales trends or technology

diffusion. Without accounting for saturation and heterogeneous lifetimes, EV stock growth would be overstated, and the timing of infrastructure and CRM requirements mischaracterised (Abdul-Manan et al., 2022; Jones et al., 2020; Watari et al., 2019a). For large emerging economies undergoing rapid, multi-modal electrification, integrating saturation and turnover dynamics is therefore essential for realistic planning.

4.2. Charging and battery demand

India's charging and battery demand patterns reflect the structural characteristics of its diverse EV transition. The expansion of SCs is driven primarily by two-wheelers and auto-rickshaws, which dominate the EV fleet and rely heavily on low-power home and neighbourhood charging. Similar SC-heavy transitions have been observed in Southeast Asian cities with comparable mobility and affordability constraints (Gupta et al., 2023; TERI, 2019). As these modes approach saturation, the relationship between new charger deployment and EV growth becomes less linear, making utilisation efficiency increasingly important. In contrast, electric cars shape the long-term growth of FCs and battery demand because of their larger battery capacities and longer-range usage. This aligns with patterns in Europe, China, and North America, where private cars drive most of the need for FC networks and high-capacity batteries (Baumgarte et al., 2021; Golab et al., 2022; IEA, 2023). For India, the key difference is timing: FC demand rises from a low baseline and must be integrated into an infrastructure system historically built around small vehicles and SCs. These structural divergences lead to distinct infrastructure challenges. FC-intensive systems in Europe and the U.S. face peak-load stress and require substantial grid reinforcement (Baumgarte et al., 2021; Town et al., 2022). India instead faces the possibility of SC overcapacity if charger rollout exceeds the slower post-saturation growth of two-wheelers and auto-rickshaws. Evidence from international charging markets indicates that overprovisioning can create stranded assets when early-adopting modes plateau (Bianchin et al., 2021). Balancing early deployment with long-term utilisation is therefore essential, particularly for SCs.

Battery demand trajectories further differentiate India from car-dominated EV systems. While electric cars become the largest contributors to total battery demand, consistent with global findings that long-range cars dominate cumulative CRM requirements (Habib et al., 2020; Xu et al., 2020), India continues to require large volumes of small, low-cost batteries for two- and three-wheelers. Consistent with the Results, two-wheelers dominate new battery demand around 2030, while cars become dominant by 2050 because of much larger pack sizes (Fig. 3). This dual demand structure contrasts with the EU or U.S., where light-duty vehicles (LDVs) largely determine battery market dynamics (Rottoli et al., 2021; Sockeel et al., 2021). India's manufacturing ecosystem must therefore scale in two directions: high-volume production of compact batteries and gradual expansion of capacity for large automotive packs. These outcomes highlight methodological implications. Incorporating mode-specific saturation levels and charger-to-vehicle utilisation ratios into DMFA avoids overestimation of SC needs and underestimation of FC growth. Static assumptions, by contrast, would misrepresent infrastructure requirements and distort long-term CRM assessments. The results, therefore, reinforce the importance of dynamic, mode-linked modelling for emerging economies with diverse passenger transport fleets.

4.3. CRM demand

India's CRM demand trajectory illustrates how electrification in a structurally diverse transport system generates large, long-term material requirements even when many vehicles are relatively small and resource-efficient. This outcome arises because aggregate CRM needs are shaped not only by per-unit intensities but also by fleet size, turnover, and battery chemistry. As electrification expands, cumulative

demand for lithium, cobalt, nickel, manganese, and copper rises across all scenarios, reflecting broader global findings that EV transitions significantly increase CRM requirements (Habib et al., 2020; Hache et al., 2019; Jones et al., 2020; Løvik et al., 2021; Song et al., 2019). Across all years and scenarios, batteries contribute nearly all lithium, nickel, and cobalt demand and more than 95% of manganese demand, while vehicle bodies supply approximately 73–81% of copper demand and chargers contribute less than 0.4%, confirming that battery chemistries overwhelmingly determine overall CRM trajectories. These results matter because they show that India's resource pressures grow even when early electrification is led by two-wheelers and auto-rickshaws, segments typically viewed as materially light. While cross-mode behavioural shifts could influence long-term CRM requirements, such interactions lie outside the scope of this national-scale stock–flow model.

The long-term shift in CRM pressure from small vehicles toward electric cars is particularly important. As two-wheelers and auto-rickshaws taper toward saturation, their CRM contributions level off, making cars and buses the dominant drivers of future material demand. Cars require higher-capacity batteries, most commonly NMC-based chemistries rich in nickel, cobalt, and lithium (Dunn et al., 2021; Xu et al., 2020). This mirrors global evidence that long-range EVs disproportionately shape cumulative CRM requirements despite forming a smaller share of total EVs (Habib et al., 2020; Hache et al., 2019). For India, this means that even moderate shifts in car adoption rates can significantly alter long-term national CRM needs. Copper becomes increasingly critical because it is required in EVs, batteries, and chargers (Backhaus, 2021; International Copper Association, 2017), while manganese gains importance through continued use of LFP chemistries in two- and three-wheelers and buses (Walvekar et al., 2022; Yang et al., 2021).

Global comparison reinforces India's strategic importance. India's CRM requirements for lithium, nickel, cobalt, and copper could reach substantial shares of today's global production by 2050, indicating that India's demand may also tighten international CRM markets through stronger competition for supply, similar to other populous emerging economies, where affordability and multi-modal travel drive EV transitions (Gupta et al., 2023; TERI, 2019). Such transitions differ from car-centric regions like the US and EU, where CRM demand largely scales with LDV electrification and where saturation constraints are rarely binding (Ghandi and Paltsev, 2020). India's combination of rapid early adoption in small vehicles and slower but more resource-intensive growth in cars makes its CRM trajectory distinct. Countries with comparable demographic and mobility patterns, such as Indonesia, Nigeria, and Ethiopia, may exhibit similar demand structures as they electrify.

The sensitivity analysis indicates that long-term CRM outcomes are most sensitive to assumptions controlling system-scale stock and turnover, particularly saturation ceilings and battery lifetime/replacement, whereas battery chemistry mainly shifts cobalt and nickel demand (Figure 6; SI-I Section 2.8). In contrast, assumptions on copper content per charger have a minor effect at the system level. This implies that the strongest levers to reduce India's primary CRM exposure are measures that limit long-run growth in demand management, durability standards, chemistry shifts pathways, and circular strategies that reduce cobalt and nickel intensity and increase the use of secondary materials.

These patterns carry important policy implications. Across scenarios, EV30@30 produces the highest CRM demand and STEPS the lowest (Figs. 4–5), with lithium, copper, and nickel emerging as the main long-run constraints by 2050 (approaching or exceeding the 2022 global benchmark in APS/EV30@30; Fig. 5). Manganese remains comparatively low in this assessment (Figs. 4–6), but India's import reliance still supports planning for domestic utilisation and downstream processing where feasible. Since batteries dominate lithium, nickel, and cobalt demand while vehicle bodies dominate copper (Fig. 4), policy should prioritise (i) battery-material supply security and (ii) copper-efficient vehicle and component value chains. Given the sensitivity ranking

(Fig. 6), the strongest risk-reduction levers are those that affect long-run stock and turnover (e.g., demand management and longer service life) and those that reduce battery replacement intensity (battery durability, repairability, and second-life pathways). Chemistry pathways mainly affect cobalt and nickel (Fig. 6), supporting targeted incentives and standards that accelerate lower-cobalt and lower-nickel options where feasible without shifting burdens elsewhere. For charging infrastructure, mode-specific standards aligned with utilisation-based national ratios (Tables S4–S7) can reduce the risk of slow-charger overbuild as two- and three-wheeler growth tapers, while ensuring adequate fast-charging rollout for cars and buses (Fig. 3). Spatial prioritisation of mining regions is outside the scope of this national stock–flow model; however, the results indicate which materials and segments should be prioritised for supply agreements, domestic processing, and staged recycling investment. India's high import dependence for lithium, cobalt, and copper (Chadha and Sivamani, 2021; Ministry of Mines, 2023) means that rising CRM needs must be matched with diversified sourcing strategies, long-term international partnerships, and clear domestic industrial pathways. While recycling can eventually ease pressure on primary supplies, recycling technologies for CRM recovery from EV batteries, motors, and power electronics remain technologically immature and are not deployed at scale, thus primary supply remains the dominant concern through most of the modelling horizon (Das et al., 2022a; Dhairiyasamy et al., 2024; UN DESA, 2025). Methodologically, the CRM outcomes highlight the value of a dynamic material flow approach that explicitly incorporates saturation, turnover, and mode-specific battery chemistries. Models relying solely on aggregate EV counts or static CRM intensities tend to mischaracterize long-term pressures, particularly in multi-modal systems where the CRM-dominant segment shifts over time (Jones et al., 2020; Watari et al., 2019a). By integrating structural saturation dynamics and heterogeneous vehicle pathways, this analysis provides a more realistic material demand outlook for India and offers a transferable framework for other emerging economies undergoing large-scale electrification.

5. Conclusions

This study assessed the electrification of India's passenger transport system from 2022 to 2050 using a saturation-aware dynamic material flow model across five major modes. The findings demonstrate that India's transition is shaped by its multi-modal mobility structure, with two-wheelers and auto-rickshaws electrifying earliest and showing tapering net stock growth from the mid-2030s as they approach their ownership saturation ceilings under the more ambitious pathways. India's mobility structure, which is dominated by two- and three-wheelers, creates electrification dynamics that differ fundamentally from the car-centric pathways observed in developed markets. As these small-vehicle segments plateau, electric cars continue expanding across the entire modelling horizon and become the primary long-term driver of battery requirements and CRM requirements, while buses and trains electrify more gradually because of their long service lifetimes.

These dynamics translate into distinct infrastructure needs and, more critically, increasing CRM requirements that shape the feasibility of large-scale electrification. Slow chargers dominate India's charging landscape because two-wheelers and auto-rickshaws remain the largest EV categories through 2050, while fast-charging demand grows mainly with electric cars. Battery demand increases steadily across all scenarios, and cumulative CRM requirements rise substantially, particularly for copper, lithium, and nickel. Although smaller vehicles have lower material intensities, the overall scale of India's future EV fleet leads aggregate CRM demand to approach or exceed today's global production levels for key materials. With domestic end-of-life EV and battery volumes remaining limited until the late 2030s, primary supply is expected to dominate India's CRM demand through most of the transition.

These findings highlight the importance of policies that anticipate early saturation in two- and three-wheelers, support infrastructure that

reflects India's mode mix, and secure long-term access to CRMs through diversified sourcing and strategic partnerships. Consistent with results, the most effective levers to reduce India's primary CRM exposure are those that target lithium, copper, and nickel supply security, extend battery lifetime (reducing replacement demand), and accelerate feasible chemistry and circular-economy pathways that reduce cobalt and nickel intensity. These measures will be essential for supporting India's electrification efforts while reducing exposure to global supply constraints. As the global shift to electric mobility accelerates, effective strategies must reflect regional differences in mobility patterns, resource availability, and infrastructure readiness. Insights from diverse national contexts, including multi-modal systems such as India's, will be essential for developing robust and globally relevant electrification pathways.

CRedit authorship contribution statement

Deepjyoti Das: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Ljunggren:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **Pradip P. Kalbar:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Supplementary Information 1 (SI-I) provides data, methods, and model details. Supplementary Information 2 (SI-II) contains figure data. The model and base data are available on reasonable request.

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