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DOI
10.1016/j.resconrec.2025.108646

Publication date
2026

Document Version
Final published version

Published in
Resources, Conservation and Recycling

Citation (APA)
Chen, Z., Kleijn, R., Zhang, C., & Lin, H. X. (2026). Fuel cell and electric vehicles: Resource use and associated environmental impacts. *Resources, Conservation and Recycling*, *226*, Article 108646. https://doi.org/10.1016/j.resconrec.2025.108646

Resources, Conservation & Recycling 226 (2026) 108646

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Fuel cell and electric vehicles: Resource use and associated environmental impacts

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ARTICLE INFO

Keywords:
Electric vehicles (EVs)
Fuel cell vehicles (FCVs)
Material demand
Environmental trade-offs
Platinum-group metals (PGMs)
Low-carbon transition
Critical raw materials

ABSTRACT

Achieving transport decarbonization depends on electric vehicle (EV) and fuel cell vehicle (FCV) deployment, yet their material demands and impacts vary by vehicle type. This study explores how powertrain preferences in light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) shape future resource use and material-related environmental outcomes. Using dynamic material flow analysis and prospective life cycle assessment, we assess three scenarios. In the S3 EV-dominant scenario, 2050 lithium and cobalt demand rises by up to 11.9-fold and 1.8-fold relative to 2020, with higher global warming and human toxicity impacts. The S2 FCV-dominant scenario leads to a 21.7-fold increase in platinum-group metal demand, driving up freshwater ecotoxicity and particulate emissions. A balanced S1 scenario, EVs in LDVs and FCVs in HDVs, yields moderate material demand and environmental burdens. These findings demonstrate that no single pathway can fully resolve material-related impacts, while combining EVs and FCVs across LDVs and HDVs enables a more balanced and sustainable transition.

1. Introduction

Decarbonization of the transportation sector is a critical component of global efforts to mitigate climate change and achieve carbon neutrality(Wang et al., 2025). Road transportation alone contributes approximately 14–20 % of the total global greenhouse gas (GHG) emissions(Rajashekara, 2023; Rigogiannis et al., 2023), necessitating urgent transitions away from fossil-fuel-powered internal combustion engine vehicles (ICEVs) toward zero-emission vehicle alternatives. Among the most promising solutions are electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs), both of which have gained considerable attention as potential pathways for sustainable mobility (Chakraborty et al., 2022; W. Zhang et al., 2023).

EVs have experienced rapid growth, largely driven by improvements in lithium-ion battery technology, expanding charging infrastructure, and declining battery costs(Miao et al., 2019; Pesaran, 2023; Xu et al., 2025). They offer high energy efficiency and lower operational costs than conventional ICEVs, particularly when powered by renewable electricity(Koniak et al., 2024; Zaino et al., 2024). However, EVs face limitations such as long charging times, range anxiety, and declining battery performance over time, particularly for heavy-duty applications (Khalid et al., 2022; Sujan et al., 2022). FCVs, by contrast, leverage hydrogen as an energy carrier and proton-exchange membrane fuel cells (PEMFCs) or solid oxide (SOFC) to generate electricity for propulsion (Binti Awang Mat et al., 2017; Pardhi et al., 2022). Their key advantages include shorter refueling times and higher energy density, making them particularly suitable for long-haul transportation and heavy-duty applications(Aminudin et al., 2023; Cullen et al., 2021). However, FCVs remain at an earlier stage of market adoption compared to EVs, with challenges including high vehicle costs, and the need for widespread

Abbreviations: EV, Electric Vehicle; BEV, Battery Electric Vehicle; PHEV, Plug-in Hybrid Electric Vehicles; ICEV, Internal Combustion Engine Vehicle; LDV, Light-Duty Vehicle; HDV, Heavy-Duty Vehicle; PGM, Platinum Group Metal; LCA, Life Cycle Assessment; p-LCA, Prospective Life Cycle Assessment; MFA, Material Flow Analysis; d-MFA, Dynamic Material Flow Analysis; GWP, Global Warming Potential; FETP, Freshwater Ecotoxicity Potential; HTPc, Human Toxicity Potential, Carcinogenic; PMFP, Particulate Matter Formation Potential; PEMFC, Proton Exchange Membrane Fuel Cell; SOFC, Solid Oxide Fuel Cell; MDCs, More Developed Countries; LDCs, Less Developed Countries; REEs, Rare Earth Elements; Li, Lithium; LFP, Lithium Iron Phosphate; NCA, Lithium Nickel Cobalt Aluminum Oxide; NMC, Lithium Nickel Cobalt Manganese Oxide; Co, Cobalt; Ni, Nickel; Mn, Manganese; Pt, Platinum.

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https://doi.org/10.1016/j.resconrec.2025.108646
Received 7 April 2025; Received in revised form 26 August 2025; Accepted 14 October 2025
Available online 25 October 2025

hydrogen infrastructure development (Greene and Duleep, 2013; Miotti et al., 2017; Xun et al., 2022).

The distinct advantages and limitations of EVs and FCVs have led to ongoing discussions about which technology would provide greater environmental and societal benefits in the long term. While earlier discussions debated the long-term sustainability of EVs and FCVs, particularly regarding trade-offs in energy efficiency, resource availability, and environmental impacts, EVs have become widely recognized as the better option for passenger cars due to their higher efficiency and lower overall environmental footprint(Miotti et al., 2017). However, for heavy-duty applications, the discussion remains open, with FCVs potentially playing a complementary role in specific use cases(Farooq and Cora, 2024; Setiawan and Setiyo, 2024). This uncertainty has driven extensive research in the academic community, with studies exploring the economic viability, scalability, and environmental footprint of each automotive technology(De Wolf and Smeers, 2023; Lei, 2024; W. Zhang et al., 2023). Some studies suggest that FCVs might become cost-competitive with EVs by 2030, driven by advancements in hydrogen production, fuel cell efficiency, and economies of scale (Aminudin et al., 2023; Li and Kimura, 2021). Some other studies suggest that the two technologies are not mutually exclusive but complementary, advocating for a multi-technology approach to decarbonization. EVs and FCVs play strategic roles depending on energy infrastructure, regional policies, and vehicle application needs(Aguilar and Groß, 2022; Andreassen and Rosendahl, 2022; W. Zhang et al., 2023).

Beyond economic, infrastructural, and environmental footprint considerations, evaluating the feasibility and sustainability of large-scale zero-emission vehicle adoption necessitates thorough research on material resource demands(Czerwinski, 2022; He et al., 2024; B. Jones et al., 2020). EVs rely heavily on lithium (Li)(Xiang et al., 2025) and, for some battery chemistries, on cobalt (Co) and nickel (Ni), which are associated with supply chain constraints, geopolitical risks, and significant environmental impacts during extraction and processing (The Role of Critical Minerals in Clean Energy Transitions, n.d.). The mining and refining of these metals are highly energy-intensive, leading to substantial emissions, water consumption, and toxic waste generation (Kalungi et al., 2024; Llamas-Orozco et al., 2023). FCVs, in contrast, depend on platinum-group metals (PGMs) for fuel cell catalysts, with large-scale production requiring substantial PGM inputs. Palladium and platinum mining also involve high energy use, significant land disturbance, and freshwater contamination (Kosai et al., 2021; Miotti et al., 2017). As demand for batteries and fuel cells grows, the supply of these critical materials must scale accordingly, which amplifies resource depletion, emissions from mining operations, and overall environmental burdens. Many scholars have conducted research on this topic. Some examined the future demand for critical metals needed for EVs, and the associated and environmental impact(Esiri et al., 2023; Habib et al., 2020). Other researchers have estimated the potential PGM requirements for future FCVs(Tong et al., 2022; C. Zhang et al., 2023a).

However, most existing research has examined the resource demands of EVs and FCVs in isolation, with few studies providing a comprehensive comparative analysis of how different technology adoption pathways impact future mineral resource demand. Additionally, most studies focus either on light-duty vehicle (LDV) or heavy-duty vehicle (HDV) electrification, rather than considering both as an integrated system (H. Hao et al., 2019a; L. Jones et al., 2020; Maani et al., 2025; Xu et al., 2020). While some researchers have explored the material requirements of EVs and FCVs across all vehicle segments, the influence of diverse technological trajectories of FCVs and other electric powertrains has not been fully considered (C. Zhang et al., 2023b). A limited number of studies have directly compared how different FCV and EV adoption scenarios affect future metal demand, considering both HDV and LDV market penetration (H. Hao et al., 2019b). However, these studies primarily focus on PGMs, without assessing the broader demand for other critical metals or the environmental impacts associated with their production. Given these research gaps, a comprehensive evaluation of material demand under different technological pathways is essential for understanding the long-term sustainability of zero-emission vehicle adoption. A comparative analysis that integrates both FCV and BEV development trajectories across LDV and HDV markets, while accounting for their implications on critical metal demand and environmental impacts, remains largely unexplored.

Addressing this need, this study conducts a scenario-based dynamic material flow analysis (d-MFA) to examine future resource demand from 2020 to 2050. Three distinct scenarios are considered: (1) S1 scenario, where FCVs primarily dominate the HDV market while BEVs prevail in the LDV segment; (2) S2 scenario, a fuel-cell-dominant future where FCVs become the primary technology across both LDVs and HDVs; and (3) S3 scenario, an extreme case where BEVs dominate all vehicle types. Moreover, we employ prospective life cycle assessment (p-LCA) to estimate the environmental impacts associated with the production of these critical metals, including global warming potential (GWP), freshwater ecotoxicity potential (FETP), human toxicity potential, carcinogenic (HTPc), and particulate matter formation potential (PMFP). By comparing these scenarios, this study evaluates the resource implications and environmental burdens associated with material production under varying EV and FCV market deployment scales and penetration levels, offering insights for policymakers, industry stakeholders, and researchers on the sustainable development of road transportation from a material availability perspective.

2. Methods

2.1. Overview of the methods

This study uses a material-based accounting model to estimate the future material demand for two key road transportation decarbonization technologies, EVs and FCVs, under three distinct scenarios with varying levels of EV and FCV adoption. To comprehensively assess both resource requirements and material-related environmental impacts, this study integrates d-MFA and p-LCA methods. The d-MFA model tracks the flow of critical materials through the vehicle stock, capturing the evolving demand, accumulation, and recycling potential of key battery and fuel cell components over time (Deng et al., 2023; Müller et al., 2014). Life Cycle Assessment (LCA) is a standardized methodological framework used to evaluate the environmental impacts of a product or system across its entire or partial life cycle (Santucci and Esterman, 2015). In this study, we adopt a p-LCA approach, which applies projected background conditions to capture the future environmental burdens associated with material production (Mendoza Beltran et al., 2020; Romain Sacchi et al., 2022). Unlike conventional LCA, which relies on current average background data (e.g., today's energy mix, supply chains, and emissions profiles), our p-LCA modifies the life cycle inventory background by incorporating forward-looking assumptions, such as decarbonized electricity and cleaner upstream processes. This approach allows us to better reflect mid- to long-term transitions in energy and industrial systems, especially when assessing low-carbon technologies. Here the p-LCA approach is applied to estimate the environmental burdens associated with material extraction and production, focusing on GHG emissions, human toxicity, freshwater ecotoxicity, and particulate matter formation. Our p-LCA focuses specifically on the material production phase, while downstream stages (vehicle manufacturing, use, and recycling) are not included in this study, they are discussed in the limitations section.

It is important to note that FCVs also incorporate small battery systems, primarily for energy buffering within the vehicle and providing auxiliary power to onboard electronics and fuel cell operation. However, their battery capacity is significantly smaller compared to EVs (Parikh et al., 2023; Sinha and Brophy, 2021; Yeow et al., 2022). Although different studies make varying assumptions regarding battery sizes, BEVs are generally assumed to have battery capacities one to three orders of magnitude larger than those of FCVs with similar vehicle weights (Ajanovic and Haas, 2019; Alonso-Villar et al., 2022). This study includes batteries in heavy-duty FCVs, while those in light-duty FCVs are not considered due to their relatively small size and negligible contribution compared to the large battery systems used in EVs. Table 1 provides details of the model structure, input parameters, and key assumptions used in the analysis.

2.2. Scenario setting

The background scenario in this study represents the total vehicle demand across all powertrain types, including ICEVs, battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs). This scenario is based on the assumptions from the previous research(C. Zhang et al., 2023b). Their model cover 16 world regions, classifying vehicles into cars, buses, LDVs/vans, and HDVs/trucks. To simplify the analysis, here we group cars and vans as LDVs, and buses and trucks as HDVs. The global vehicle stock is projected to increase to 1537 million in 2030 and 2386 million in 2050, providing the baseline for estimating the demand for different powertrain technologies across regions. See Table S2 for more details.

Building on this background scenario, this study defines three powertrain technology scenarios for EVs and FCVs to assess the material demand and associated environmental impacts of different road transportation decarbonization pathways. The S1 scenario reflects the most realistic trajectory, aligning with current market trends, while the S2 and S3 scenarios represent extreme cases.

In the S1 scenario, FCVs primarily dominate the HDV market, while BEVs and PHEVs become the prevailing technologies for LDVs. This scenario aligns with the idea that hydrogen fuel cells offer superior advantages for long-haul freight transport, given their higher energy density, faster refueling times, and lower weight constraints compared to batteries. Meanwhile, BEVs and PHEVs continue to dominate the passenger vehicle segment, driven by ongoing battery cost reductions, widespread charging infrastructure expansion, and strong urban electrification policies. This scenario reflects a balanced transition strategy, acknowledging the distinct advantages of each technology in different vehicle applications (L. Jian et al., 2020; Lin, 2024).

The S2 scenario represents a theoretical hydrogen-intensive pathway in which FCVs dominate both LDV and HDV markets by 2050. Achieving such a transition would require substantial progress in hydrogen production, distribution infrastructure, and fuel cell technology, supported by consistent and large-scale policy and investment efforts, particularly in the HDV segment (Chapman et al., 2020; Stangarone, 2021). However, significant geopolitical, economic, and logistical barriers exist that limit the near- to mid-term scalability of FCVs, especially for LDVs. The lack of hydrogen refueling infrastructure, combined with the high cost of hydrogen production and distribution, continues to restrict consumer adoption (Greene et al. 2020). Moreover, regional disparities in policy ambition and industrial capacity further exacerbate deployment challenges. For instance, Japan and South Korea continue to support FCVs, whereas the European Union and the United States have increasingly prioritized EVs (Trencher and Wesseling 2022). In fact, global FCV sales declined by 30 % in 2023 compared to 2022, reflecting broader market hesitation and growing uncertainty about long-term viability (Collins 2024). These trends suggest that the S2 scenario should be interpreted as a counterfactual upper-bound scenario for academic exploration rather than a plausible pathway under current socio-technical conditions. For heavy-duty vehicles, corridor-based refuelling strategies along major freight routes may partially mitigate some of these adoption barriers, although large-scale deployment would still require substantial infrastructure investment and coordination(Siekmann et al., 2023).

The scenario S3 assumes a battery-dominated future, where BEVs and PHEVs become the core technologies for road transport decarbonization, leading both LDV and HDV markets. This scenario relies on continued advancements in battery technology, including higher energy

Table 1
Overview of model variables and assumptions Note: The vehicle here refers to all types of cars, including internal combustion engine vehicles (ICEVs), while two-wheel and three-wheel vehicles are excluded.

Key parameters	Descriptions
Vehicles stocks	The vehicle stocks at global and regional levels are obtained from Zhang et al. (C. Zhang et al., 2023b). This study extrapolated the investigated regions, based on data from 48 major countries in a previous study, to the global level. The projection shows that global vehicle stock will increase to 1537 million in 2030, and 2386 million in 2050.
Vehicle categories considered	Categories based on powertrain: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (BEVs), and fuel cell vehicles (FCVs) (Selvakumar, 2021). Categories based on gross vehicle weight: light-duty vehicles (LDVs), and high-duty vehicles (HDVs) (Islam et al., 2024).
Geographical scopes	Countries are classified into two categories: More Developed Countries (MDCs) and Less Developed Countries (LDCs). MDCs include Oceania (Australia, New Zealand), Western Europe, Central Europe, Japan, South Korea, Canada, and the United States. Given its ambitious goals for vehicle electrification, China is also considered part of MDCs. LDCs consist of Southeast Asia (Malaysia and Thailand), South Africa, the Rest of South America (Chile), Turkey, Mexico, India, Indonesia region (INDO), and Brazil. This classification is based on the framework of the integrated assessment model IMAGE and literatureH. (Hao et al., 2019a, H. 2019b).
Scenarios for vehicle technologies	Scenario S1: FCVs dominate the HDV market, while EVs and PHEVs dominate the LDV market by 2050. Scenario S2: FCVs dominate both HDV and LDV markets by 2050. Scenario S3: EVs and PHEVs dominate both HDV and LDV markets by 2050. The market shares in each scenario are assumed based on the literature and our estimations. See Section 2.1, Table S3-S5, and Figure S1-S3 for more details (H. Hao et al., 2019a; H. 2019b; International Energy Agency, 2023; C. Zhang et al., 2023b).
Engine power and battery capacity	The average engine power of FCVs for both LDV and HDV is assumed based on the literature (H. Hao et al., 2019b; Miotti et al., 2017). Similarly, the average battery capacities of BEV, PHEV, and FCV for LDV and HDV are estimated based on the literature (Sinha and Brophy, 2021; Xu et al., 2020). The battery capacity of light-duty FCV is not considered(Miotti et al., 2017). See Table S6 for more details.
Vehicle and battery lifetime	The average lifetime of all vehicle types is assumed to be 15 years(Iyer et al., 2023). Both battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCVs) contain battery systems. For light-duty vehicles (LDVs), the battery lifetime is assumed to match the vehicle lifetime (15 years), regardless of whether the vehicle is a BEV or an FCV. In contrast, HDVs have a shorter average battery lifespan of 8 years, necessitating battery replacement within the vehicle's optional lifetime. Additionally, the fuel cell lifetime in FCVs is also assumed to align with the vehicle lifespan (15 years). Weibull distribution is used to simulate the lifetime distribution of vehicles(Liang et al., 2023; Rith et al., 2018; Xu et al., 2020). Further details of these assumptions can be found in Table S8 of the SI.
Battery and fuel cell markets	For hydrogen fuel cell technologies, the proton-exchange membrane fuel cell (PEMFC) is currently the only type considered suitable for automotive applications and is expected to dominate the FCV market (Booto et al., 2021; Manoharan et al., 2019). For automotive battery technologies, lithium nickel cobalt aluminum oxide (NCA), lithium nickel cobalt manganese oxide (NCM111, NCM523, NCM622, NCM811, NCM911), and lithium iron phosphate (LFP) batteries are analyzed, with their market shares estimated based on existing literature sources(Maisel et al., 2023; Xu et al., 2020; C. Zhang et al., 2023b). More details can be found in Figure S7 of the SI.

(continued on next page)

Table 1 (*continued*)

Key parameters	Descriptions
Material intensities of battery	The battery material intensities are derived from the existing literature(Davies et al., 2024; Liang et al., 2023; Usai et al., 2022; Xu et al., 2020; Zeng et al., 2022). See Table S7 for more details.
PGM loading of FCVs	The reduction of PGM load and cheaper metal catalysts in FCVs are being actively promoted due to the high cost of PGM. The PGM load of fuel cells is assumed to present a downward trend. The average PGM load in 2020 is around 0.3 g/kw(Zhang et al., 2024), is assumed to be 0.125 g/kw in 2030(Zhang et al., 2024), then decreases to 0.1 g/kw in 2040 and stays constant(Reverdiau et al., 2021).
Recycling scenario	The recycling rate of PGM is assumed to increase from the current 50 % to 90 % in 2050 based on literature (H. Hao et al., 2019b; Reverdiau et al., 2021). The recycling rates for Li, Ni, Co, and Mn from batteries are derived from the World Bank and other related literature, as shown in Figure S8 (Bae and Kim, 2021; Chen et al., 2024; Davies et al., 2024; Hund et al., 2020; Watari et al., 2019; Zeng et al., 2022).

density, faster charging, and longer lifespans, alongside cost reductions and large-scale charging infrastructure deployment(Crabtree, 2019; Muratori et al., 2021). Given the increasing efficiency and declining costs of batteries, this scenario explores the implications of a transport system where battery technology plays a central role in emission reduction efforts.

The market shares of different vehicle types in the S1 and S2 scenarios are derived from the D1 and D2 scenario assumptions in existing study (H. Hao et al., 2019a; H. 2019b). The S1 and S2 scenarios are designed to align with these assumptions, with S1 drawing from the D1 scenario and S2 from the D2 scenario, ensuring consistency in the projected powertrain distributions across different regions. Each group follows distinct market share trajectories for LDVs and HDVs, and to maintain consistency with their classification, we further group the 16 world regions from the background scenario into two categories: More Developed Countries (MDCs) and Less Developed Countries (LDCs). MDCs include Oceania (Australia, New Zealand), Western Europe, Central Europe, Japan, South Korea, Canada, and the United States, as well as China, given its strong vehicle electrification policies. LDCs consist of Southeast Asia (Malaysia, and Thailand), South Africa, the Rest of South America (Chile), Turkey, Mexico, India, Indonesia, and Brazil. More details on the assumptions of the S1 and S2 scenarios can be found in Tables S3 and S4 of the SI. For the S3 scenario, LDV market shares remain the same as in S1, while the HDV segment is estimated based on multiple sources. The ICEV share follows the assumption in S1 and S2, reaching 0 % by 2050. FCV penetration is expected to remain below 15 %("EVO Report 2024," 2024) due to infrastructure and cost barriers. Given the higher cost tolerance in MDCs, we assume FCVs reach 15 % in MDCs and 10 % in LDCs. The remaining market share in the S3 is then allocated among BEVs, PHEVs, and HEVs based on the relative shares from Fig. 1 of the supplementary material in the literature (H. Hao et al., 2019a; H. 2019b; International Energy Agency, 2023; C. Zhang et al., 2023b). The EV share is calculated as 100 % minus the ICEV and FCV shares, then multiplied by the respective proportions of BEVs, PHEVs, and HEVs from the reference study to determine their final market shares in the HDV segment. Finally, the market shares of different powertrain technologies under each scenario are applied to the total vehicle stock projections from the background scenario for each region, yielding the total number of vehicles by powertrain type across different regions and vehicle categories (LDVs and HDVs) from 2020 to 2050. For more details on the global powertrain mix of LDVs and HDVs in the S3 scenario, see Table S5 for more details. Moreover, this study includes a recycling scenario to evaluate the potential of circular economy strategies in mitigating material supply risks. The recycling rates for each material are derived from existing literature (Bae and Kim, 2021; Chen et al., 2024; Davies et al., 2024; H. Hao et al., 2019b; Hund et al., 2020; Reverdiau et al., 2021; Watari et al., 2019; Zeng et al., 2022), as shown in Figure S8 in the SI.

2.3. Battery capacities and fuel cell power

The total global stock of battery capacity and fuel cell capacity is estimated based on the number of vehicles across different categories, each multiplied by its corresponding battery capacity or fuel cell power per vehicle. This study considers both LDVs and HDVs, further categorized into BEVs, PHEVs, and FCVs. The total number of each vehicle type is determined by applying the assumed market shares of BEVs, PHEVs, and FCVs under different technology scenarios to the projected total vehicle stock.

To determine the battery capacity and fuel cell power per vehicle, we collect data from existing literature on different powertrain technologies (Hao et al., 2019b; Miotti et al., 2017; Sinha and Brophy, 2021; Xu et al., 2020). For each vehicle type, the average battery capacity or fuel cell power is calculated from multiple sources and used as the starting value for 2020. As energy storage technologies improve over time, the required capacity per vehicle tends to decrease due to efficiency gains. Therefore, by 2050, the battery capacity per vehicle is assumed to reach the lowest value reported in the literature. This assumption reflects advancements in battery energy density, powertrain efficiency, and

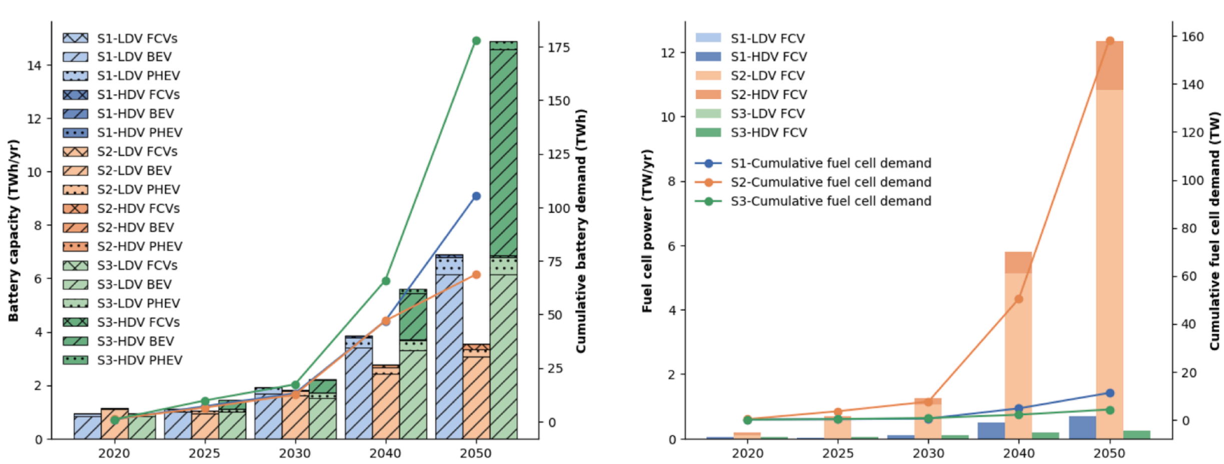

Fig. 1. Demand for battery capacity and fuel cell power in the S1, S2, and S3 scenarios. (a) Battery demand for electric vehicles (EV). (b) Fuel cell demand for fuel-cell vehicles (FCVs).

system optimization, which reduce the required capacity per vehicle while maintaining or improving driving range and performance. The specific values for battery capacity and fuel cell power used in this study, along with their literature sources, are provided in Table S2 of the Supplementary Information (SI).

2.4. Material demand

Then stock-driven d-MFA (Göswein et al., 2019; Müller et al., 2014) is employed to estimate the annual inflow of vehicles and the corresponding battery (TWh) and fuel cell (TW) capacities. The stock dynamics are governed by a convolution equation, which accounts for newly added, in-use, and decommissioned batteries and fuel cells:

$$Inflow_t = Stock_t - Stock_{t-1} + Outflow_t \tag{1}$$

$$Outflow_t = \sum_{j=t_0}^{j=t-1} inflow_j \times (1 - S_{t-j}) \tag{2}$$

where $Inflow_t$ and $Inflow_j$ denote the number of newly added batteries and fuel cells in year t and j, respectively. $Stock_t$ denotes the total in-use stock of batteries and fuel cells in year t, while $Outflow_t$ corresponds to the number of decommissioned batteries and fuel cells in year t. S_{t-j} refers to the survival function, which models the probability that a vehicle remains in operation t-j years after its introduction. A Weibull distribution is applied to estimate battery and fuel cell retirements (see Table 1 and Table S7 in the Supplementary Information for further details)(Liang et al., 2023; Rith et al., 2018; Xu et al., 2020).

The estimated battery and fuel cell capacities are converted into material flows and stocks based on their respective compositions. The battery market comprises various chemistries, including lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel cobalt manganese oxide (NMC), each with distinct material compositions and densities. Using data from the IEA and other literature sources (Maisel et al., 2023; Trends in electric vehicle batteries – Global EV Outlook 2024 – Analysis, n.d.; Xu et al., 2020; C. Zhang et al., 2023b), the total capacity stock for each battery type is estimated (see Figure S7 for details).

The battery inflow is multiplied by the market share of each battery chemistry to determine the annual capacity additions for each chemistry type. The material intensity (MI) values for battery chemistries and PGM loading data for fuel cells are then applied to the battery and fuel cell capacities, respectively, to calculate the annual demand for critical materials under different technology scenarios. The MI values for battery chemistries(Davies et al., 2024; Liang et al., 2023; Usai et al., 2022; Xu et al., 2020; Zeng et al., 2022) and fuel cells(Zhang et al., 2024) are derived from existing research (see Table S8 and Figure S9 for detailed data).

2.5. Material-related environmental impacts assessment

A p-LCA approach (Mendoza Beltran et al., 2020; Usai et al., 2021) is applied to evaluate the environmental impacts associated with material production for EV and FCV deployment. As this study primarily focuses on the environmental impacts associated with the production of battery and fuel cell materials for EVs and FCVs, only the production stage of relevant materials is considered. This study uses the ecoinvent 3.9.1 database(Wernet et al., 2016) and Premise(Sacchi et al., 2022) as the foundational life cycle inventory (LCI) databases and adopts the Shared Socioeconomic Pathway 2 (SSP2) scenario from the REMIND (Regionalized Model of Investment and Development) model (Baumstark et al., 2021) to represent future technological and energy system developments. SSP2 represents a “middle-of-the-road” development trajectory, where economic growth, technological progress, and environmental policies follow historical trends without extreme disruptions. It is widely used as a reference scenario in prospective assessments. Activity Browser is used to support dynamic inventory modeling over time, enabling the analysis of future changes in material-related environmental footprints (Steubing et al., 2020; Steubing and de Koning, 2021).

We focus on four key environmental impact categories that are particularly relevant to the production of materials required for EV and FCV deployment. Given the resource-intensive nature of metal extraction and processing, these impact categories are selected based on their significant sensitivity to material production. Global Warming Potential (GWP100) is assessed to quantify the GHG emissions associated with metal extraction, refining, and manufacturing, as these processes are highly energy-intensive and reliant on carbon-intensive inputs(Kosai and Yamasue, 2019). FETP is included due to the substantial environmental burden posed by mining and refining activities, which generate metal leaching and toxic effluents that contaminate aquatic ecosystems (Bori et al., 2017; Byrne et al., 2012; Flexer et al., 2018). HTPc is considered to evaluate the exposure risks associated with carcinogenic substances released during metal production, particularly in refining processes that involve heavy metals and chemical treatments (Salvatore Gallicchio and Harper, 2021). Lastly, PMFP is analyzed to capture the impact of airborne particulate emissions resulting from ore processing, combustion-related activities, and transportation within supply chains (Davourie et al., 2017; Lee, 2020). These categories provide a comprehensive assessment of the material-related environmental burdens associated with the transition to low-carbon transportation technologies.

2.6. Sensitivity analysis

To test the robustness of our results, a one-at-a-time sensitivity analysis is performed to determine how the variation of key parameters affect the environmental impacts across impacts categories and scenarios. Three key parameters are examined: (i)lifetime of both EV and FCV is assumed to increase 20 % (Sanclemente Crespo et al., 2022); (ii) battery capacity and fuel cell power per vehicle is assumed to rise linearly, reaching +20 % relative to the baseline in 2050(“Horizon to deliver 370 kW PEMFC stacks for heavy-duty vehicles,” 2019; Xu et al., 2020); and (iii) the default battery chemical market is replaced by a high-NCM trajectory in which NCM chemistries dominate the EV market by 2050(Xu et al., 2020; Chunbo Zhang et al., 2023b) (see Figure S11 for more details).

3. Results

3.1. Future vehicle fleet, battery, and fuel cell markets

The future global battery capacity and fuel cell power demand are modeled under three distinct scenarios, each defined by varying degrees of fuel cell and battery vehicle adoption across different vehicle segments and geographic regions (see Figures S1–S3 for details in the Supporting Information). These scenarios aim to explore contrasting technological pathways: S1 represents a balanced, realistic development trajectory, while S2 and S3 depict extreme cases favoring either fuel cell or battery dominance, respectively.

The S1 scenario represents a balanced future development pathway based on the current trajectory of FCV adoption, where FCVs primarily dominate the HDV segment, while EVs prevail in the LDV market. Fig. 1 shows that under the S1 scenario, the annual battery capacity demand is projected to reach approximately 6.9 TWh by 2050, with a cumulative demand of around 104.8 TWh from 2020 to 2050. In this scenario, most of the battery demand originates of the battery demand originates from the LDV segment, with an annual demand of 6.8 TWh (98 % of the total) in 2050, aligning with estimation ranges from other relevant research (ranging from 6.8 to 12.0 TWh)(Maisel et al., 2023; Xu et al., 2020). Within the LDV segment, BEVs account for 89.4 % of the total demand by 2050, while PHEVs contribute 9.3 % (643.2 TWh). Additionally, FCVs in the HDV segment account for 1.3 % (87.0 TWh) of the total battery demand in 2050, due to their reliance on small-capacity batteries as ignition power sources. For fuel cell power, all demand originates from the HDV market, with annual demand projected at approximately 0.9 TW in 2050.

The S2 scenario assumes a fuel-cell-dominated future, where FCVs prevail in both the LDV and HDV markets. This results in significantly lower battery demand compared to the other two scenarios, with a cumulative demand of 68.6 TWh from 2020 to 2050—only 65.1 % and 38.7 % of the total demand in the S1 and S3 scenarios, respectively. Similar to the S1 scenario, in the S2 scenario, the LDV market remains the primary contributor to battery demand. BEVs and PHEVs account for 86.9 % (3.1 TWh) and 7.3 % (0.3 TWh) of the total annual battery demand in 2050, respectively. Although FCVs are also present in the LDV market under this scenario, their contribution to battery demand is negligible due to the very small battery capacities installed in each light-duty FCV. In contrast, HDVs equipped with fuel cells require significantly larger battery packs (see Table S1 for details), primarily due to their higher power demands, regenerative braking systems, and the need for buffer energy storage to optimize fuel cell operation (Kilgore et al., 2023; Knibbe et al., 2023). As a result, the annual battery demand will reach 0.2 TWh in 2050, representing 5.7 % of the total. In the S2 scenario, annual fuel cell power demand increases nearly 65-fold, from 0.2 TW in 2020 to 12.3 TW by 2050, with a cumulative demand of 158.4 TW

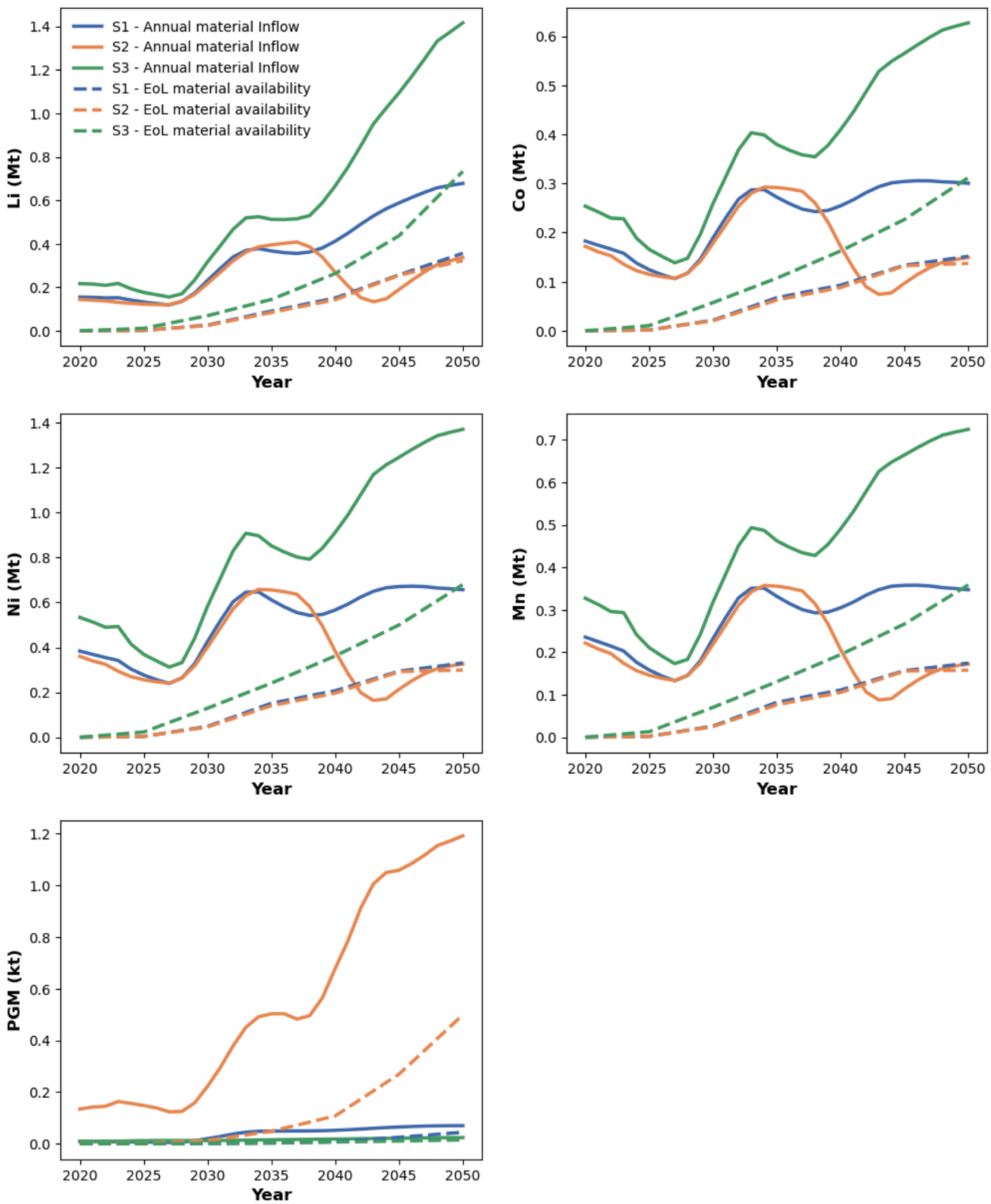

Fig. 2. Annual material flows of Li, Co, Ni, Mn, and PGMs from 2020 to 2050 in the S1, S2, and S3 scenarios.

over the 2020–2050 period. Despite the larger average fuel cell capacity in HDVs compared to LDVs, the dominance of LDVs in total numbers leads to their significant contribution, accounting for 87.7 % of annual demand in 2050, while HDVs contribute 12.3 %.

The S3 scenario represents the opposite extreme, envisioning a future where battery vehicles dominate not only the LDV market but also a significant share of the HDV market. This scenario is driven by rapid advancements in battery technology and the imperative for deep transportation sector decarbonization. As a result, battery demand in the S3 scenario surpasses that of all other scenarios, rising from 0.93 TWh in 2020 to 14.9 TWh in 2050, with a cumulative demand of 178.2 TWh over the period. The primary driver of this increase is the widespread electrification of HDVs, which require substantial battery capacity per vehicle. By 2050, HDVs are estimated to account for 52.5 % of total battery demand, based on our scenario assumptions and calculations of battery requirements for different vehicle categorized. Conversely, fuel cell power demand in the S3 scenario is minimal, as only a small share of HDVs relies on fuel cells. The cumulative fuel cell demand from 2020 to 2050 is just 4.2 TW—equivalent to 37.6 % and 2.6 % of the demand in the S1 and S2 scenarios, respectively.

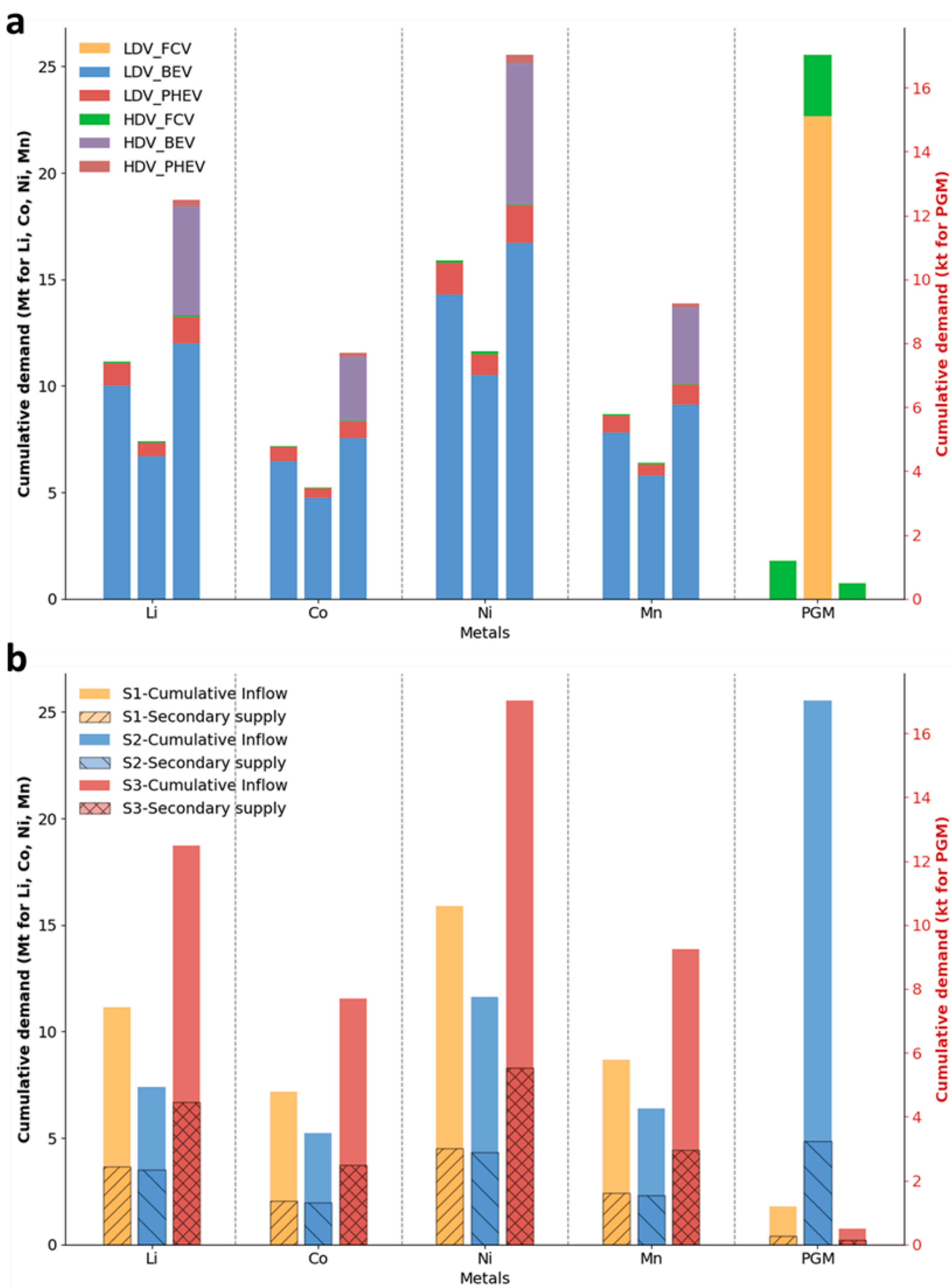

Fig. 3. Cumulative material demand from 2020 to 2050 under the S1, S2, and S3 scenarios, shown by vehicle type (a) and supply potential for secondary supply (b). Material demand is presented in Mt on the right Y-axis, except for PGMs, which are shown in kt.

3.2. Demand for critical materials

We estimate the future material demand for the transportation decarbonization transition based on the simulated future market of EVs and FCVs. Battery chemistry considered here includes LFP, NCA, and NMC. The market shares of these battery chemistries are projected based on literature estimates (see Figure S7). As shown in Fig. 2a and Figure S9, if EVs dominate the HDV segment (S1 scenario) or both the HDV and LDV segments (S3 scenario), the annual demand for critical battery materials, including Li, Co, Ni and Mn, will increase substantially from 2020 levels. Specifically, lithium demand is projected to rise by a factor of 5.5 under the S1 scenario and 11.9 under the S3 scenario, while Co, Ni, and Mn demands are expected to increase by 1.8–3.9, 1.9–4.1, and 1.6–2.4 times, respectively. This surge is driven by the higher EV market share, which requires increased battery production. Ni demand increases from around 0.4 Mt (metric ton based, used throughout) to 0.7 Mt in the S1 scenario to 1.4 Mt in the S3 scenario, while Li demand rises from 0.1 Mt in 2020 to 0.7 Mt in S1 and 1.5 Mt in the S3 scenario, equivalent to 8.4 to 16.9 times the global Li production in 2020 (0.1 Mt)(U.S. Geological Survey, 2021). By 2050, Co and Mn demand would be of the same order of magnitude, ranging from 0.3 to 0.6 Mt and 0.3–0.7 Mt, respectively. The estimated Co demand is approximately 2.3–4.5 times the Co production in 2020 (0.132 Mt) ("Cobalt Market Report 2020," n.d.). The demand for PGM remains significantly lower than that of other battery materials in S1 and S3 because of the lower market share of FCVs, which is around 0.02 in the S3 scenario and 0.1 kt in the S1 scenario. In the S2 scenario, where FCVs gradually dominate both the HDV and LDV segments, the material demand profile shifts significantly. Battery material demand initially rises but declines after 2035, returning to levels comparable to those in 2020 by 2050 In contrast, PGM demand surpasses that of all other materials and rises continuously by a factor of 21.7, increasing from 0.1 kt in 2020 to 1.2 kt in 2050, which equals 2.7 times the total PGM production of 443.2 t in 2020.(Platinum-Group Metals: 2020 Mineral Commodity Summary, n.d.).

Fig. 3a illustrates the cumulative material demand by vehicle technologies over the next three decades. A higher EV market share increases the cumulative demand for battery materials while reducing the need for PGMs. In all S1 and S2 scenarios, the majority of battery-related material demand comes from BEVs in the LDV segment, followed by light-duty PHEVs. In contrast, in the S3 scenario, battery-related material demand from heavy-duty BEVs increases slightly due to the assumed higher market share of EVs in the HDV. In S1 and S3 scenarios, all cumulative PGM demand originates from heavy-duty FCVs, as fuel cell technology is not employed in LDVs under these scenarios. However, in the S2 scenario, where FCVs dominate both LDV and HDV markets, over 85.3 % of PGM demand comes from LDVs. This is primarily due to the significantly larger fleet size and higher annual sales volume of LDVs compared to HDVs, leading to greater cumulative material demand despite their lower per-vehicle fuel cell capacity and PGM requirement.

The cumulative demand for these five critical materials is compared with their corresponding global resources and reserves to assess potential supply risks. Despite varying preferences for batteries and fuel cell technologies across the three scenarios, global proven resources for almost all materials are sufficient to meet the cumulative demand for battery and fuel cell production in the automotive sector. As of 2023, global Li reserves are approximately 28.0 Mt(U.S. Geological Survey., 2020), which is sufficient to produce all vehicle batteries by 2050, regardless of EV penetration level, with cumulative Li demand reaching 11.2 Mt in S1, 7.4 Mt in the S2, and 18.7 Mt in the S3 scenario. global Co reserves in 2023 (11.4 Mt) (Mineral commodity summaries 2024, n.d.) may be insufficient under the high EV adoption scenario (the S3 scenario), where EVs also dominate the heavy-duty vehicle market, leading to a cumulative Co demand of 11.5 Mt. However, in the S1 and S2 scenarios, Co supply is expected to be sufficient, with cumulative demand reaching 7.2 Mt in the S1 and 5.2 Mt in the S2 scenarios, respectively. For Ni and Mn, their global proven reserves (130.0 Mt and 1900.0 Mt, respectively) (Jaganmohan, 2025; Nickel Institute, n.d.) would far exceed the cumulative demand of 11.6–25.5 Mt for Ni and 6.4–13.9 Mt for Mn. Although annual PGM demand increases significantly in the fuel-cell-dominant scenario (the S2 scenarios), global mineral reserves (70.0 kt) (Natural Resources Canada, 2018) are sufficient to meet the cumulative requirement of 17.0 kt for automotive fuel cell production. This remains the case even when accounting for PGM usage in internal combustion engine vehicles (ICEVs), which is projected to reach a cumulative 1.6 kt by 2050(Liang et al., 2024).

While global reserves of Li, Co, Ni and Mn, and PGMs appear sufficient to meet cumulative demand, supply will need be ramped very quickly and supply risks persist / increase due to geopolitical, environmental, and economic factors. The extraction and processing of these materials are highly concentrated, with China dominating Ni refining and Li processing, and the Democratic Republic of Congo supplying most Co(Althaf and Babbitt, 2021; van den Brink et al., 2020). Trade policies, including export restrictions and geopolitical tensions, further threaten supply stability(Yan et al., 2020). In addition to the automotive sector, these critical materials are essential for industries such as electronics, renewable energy storage, and aerospace, increasing competition for supply(Kim et al., 2022). The growing demand across multiple sectors could strain production capacity, further heightening supply risks.

Recycling of critical metals from end-of-life batteries and fuel cells can partially mitigate reliance on primary resource extraction. As shown in Fig. 2, the annual availability of recyclable materials in 2050 is substantial and, for several metals, even exceeds their current global production levels. For instance, in the FCV-dominant S2 scenario, the projected outflows of cobalt (0.14 Mt), lithium (0.32 Mt), manganese (0.16 Mt), and PGMs (0.50 kt) surpass their respective 2020 production levels of approximately 0.14 Mt, 0.08 Mt, 0.02 Mt, and 0.44 kt (Yao 2024; Global lithium production 2024 ; Manganese Statistics and Information ; Platinum-Group Metals Statistics and …). For other metals, such as nickel, the 2050 outflow (0.30 Mt) remains below the 2020 global production (2.5 Mt)(International Nickel Study Group), but still represents a non-negligible share of future supply (around 13 %). When compared to their annual material demand in 2050, the recycling potential of key battery metals, particularly under the S2 scenario, could nearly match the total demand, highlighting the theoretical importance of secondary supply. These comparisons underscore the significant potential of end-of-life materials to offset primary extraction. However, actual recovery remains constrained by collection inefficiencies, processing losses, and economic barriers. Consequently, although recycling can reduce primary demand, its realized contribution is modest in most scenarios. Over the 2020–2050 period, cumulative recycled lithium is projected to offset only 31.9–47.6 % of total demand, while cobalt recovery accounts for just 20.2–24.7 %. For nickel and manganese, secondary supply could meet 27.5–37.4 % and 28.1–36.3 % of demand, respectively. In the case of PGMs, recycling may provide only 18.6–28.1 % of cumulative demand. While these percentages demonstrate the value of recycling, they also indicate that a substantial portion of future supply will still need to be met through primary extraction.

3.3. Environmental impacts

In addition to assessing how transition dominated by FCV and BEV affect material demand, this study further examines the environmental impacts of the material requirements of battery and fuel cell technologies under the SSP2 ("middle-of-the-road") energy mix framework across the three technology scenarios. The decision to prioritize either battery- or fuel-cell-dominant pathways leads to distinct trade-offs between emissions, toxicity, and pollution impacts Fig. 4 presents the cumulative environmental impacts for 2020–2050 in four categories: GWP, FETP, HTPc, and PMFP. The findings indicate that while each scenario introduces a different material-related environmental burden, the choice between battery- and fuel-cell-dominant pathways results in distinct

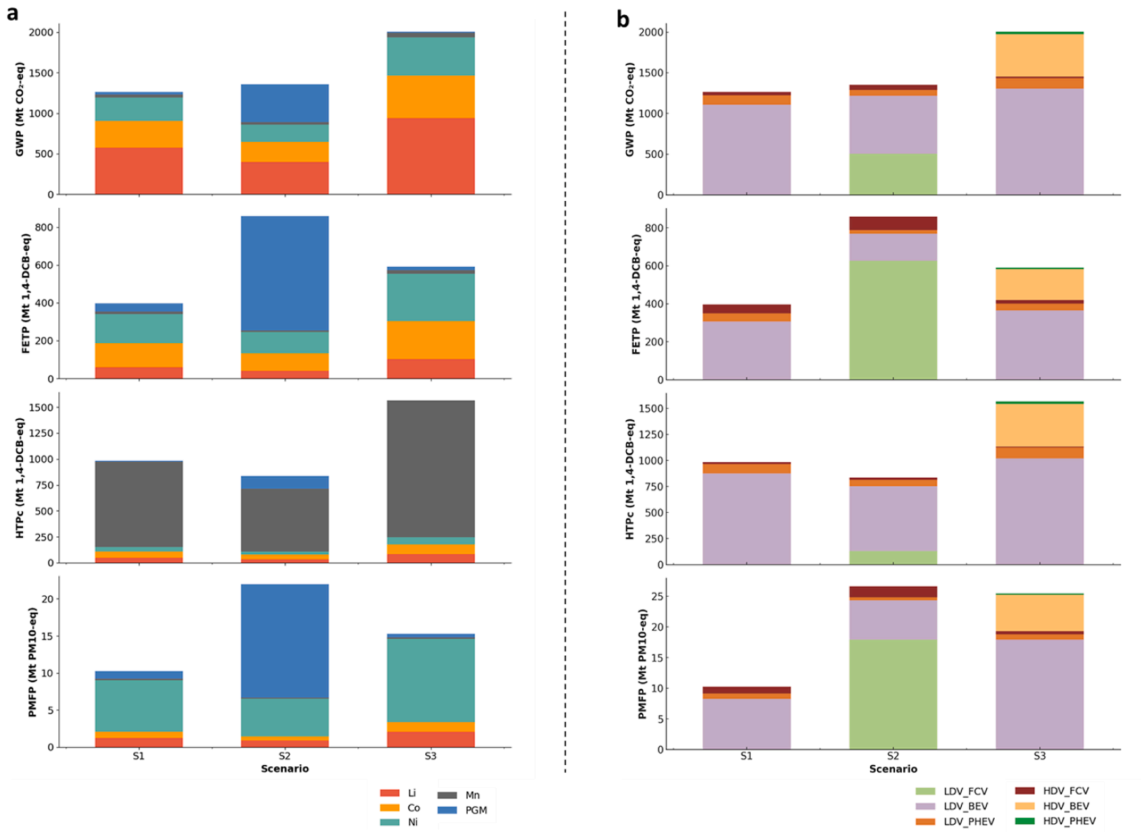

Fig. 4. Cumulative material-related environmental impacts under the SSP2 energy mix from 2020 to 2050, categorized by material type (a) and vehicle type (b) across the S1, S2, and S3 scenarios. Abbreviations: GWP - Global Warming Potential; FETP - Freshwater Ecotoxicity Potential; HTPc - Human Toxicity Potential, Carcinogenic; PMFP - Particulate Matter Formation Potential.

trade-offs between emissions, toxicity, and pollution impacts.

In the S1 scenario, where FCVs primarily dominate the HDV market while EVs lead the LDV segments, the environmental impacts remain relatively balanced across all categories. GWP and HTPc are moderate (1264.6 Mt CO_2-eq and 982.8 Mt 1,4-DCB-eq, respectively), as battery-related emissions from Ni, Li, and Co production are lower than in S3, while fuel-cell-related PGM demand is lower than in the S2 scenario. FETP and PMFP impacts (396.5 Mt 1,4-DCB-eq and 10.3 Mt PM10-eq respectively) are also moderate since neither battery metals nor PGMs are extracted at extreme levels. This suggests that a mixed technology transition could mitigate some extreme environmental burdens, though it still requires substantial resource extraction and processing.

In the S2 scenario, where FCVs dominate both LDV and HDV segments, GWP and HTPc (1353.3 Mt CO_2-eq and 835.5 Mt 1,4-DCB-eq, respectively) are comparable to those in S1, indicating that fuel cell technology does not lead to a significant advantage in reducing climate and human toxicity impacts compared to a balanced FCV-EV transition. However, FETP and PMFP increase significantly (859.2 Mt 1,4-DCB-eq and 21.9 Mt PM10-eq respectively), primarily due to the high demand for PGMs in fuel cells. The mining and refining of PGMs introduce substantial environmental burdens, particularly in terms of freshwater contamination and particulate matter emissions from industrial extraction and processing. These results highlight a critical trade-off: while the S2 scenario reduces reliance on battery metals and the associated toxicity from Co and Ni extraction, it introduces new environmental challenges related to the resource-intensive production of PGMs used in fuel cells.

In the S3 scenario, where EVs dominate both LDV and HDV segments, the environmental profile shifts toward higher GWP and HTPc (2005.3 Mt CO_2-eq and 1567.3 Mt 1,4-DCB-eq, respectively), reflecting the intensive material processing required for large-scale battery deployment. Compared to the S1scenario, Ni and Co contribute a much larger share to GWP and toxicity-related impacts, increasing overall emissions and health risks from mining and refining. However, the S3 scenario exhibits lower FETP (590.1Mt 1,4-DCB-eq) and PMFP (15.3 Mt PM10-eq) compared to the S2 scenario, as it avoids the substantial PGM-related emissions seen in fuel cell production. These results indicate that while EV-dominant pathways reduce the operational emissions of vehicles, their material footprint presents a significant sustainability challenge.

It is important to note that these environmental impact assessments are limited to material production and do not account for the full life cycle impacts. Many existing LCA studies that incorporate the vehicle use phase indicate that GHG emissions from FCVs are highly dependent on the electricity source used for hydrogen production. When hydrogen is generated from renewable electricity, the lifecycle GHG emissions of FCVs are comparable to or slightly higher than those of battery electric vehicles (BEVs)(Chen et al., 2019; Desantes et al., 2020; Üçok, 2023). However, if hydrogen is produced from fossil fuels, FCVs can have significantly higher GHG emissions (Syré et al., 2024).

These findings suggest that neither a fully battery-electric nor a fully fuel-cell-dominant pathway eliminates environmental concerns related to their material production—each scenario redistributes environmental burdens rather than eliminating them. While the S3 scenario exhibits the highest material-related emissions and toxicity risks, this must be weighed against the lower operational emissions of BEVs. Over their lifetime, many studies show EVs produce lower GHG emissions due to their higher energy efficiency and lower electricity consumption during use, particularly when powered by low-carbon energy sources (Delucchi et al., 2014; Nealer and Hendrickson, 2015). The S2 scenario introduces greater material-related freshwater toxicity and particulate matter pollution due to its reliance on PGMs. The S1 scenario, as a more balanced transition, avoids the extreme impacts of either approach, although it still requires substantial resource extraction. These findings further confirm that EVs and FCVs serve complementary roles in vehicle decarbonization and should be developed in coordination to maximize environmental sustainability and minimize resource constraints.

3.4. Sensitivity results

The sensitivity analysis (Fig. 5a) reveals that, in all scenarios, cumulative environmental outcomes are most responsive to changes in battery market share assumptions, while lifetime and per-vehicle battery capacity and fuel cell power play a secondary role. As shown in Fig. 5, extending the average lifetime of batteries and fuel cells by 20 % leads to a reduction of 11–13 % across all four cumulative environmental impact categories: climate change, freshwater ecotoxicity, carcinogenic human toxicity, and particulate matter formation. Increasing battery capacity and fuel cell power per vehicle by 20 % results in a moderate rise in cumulative environmental impacts, ranging from 5 % to 8 % depending on the category. By contrast, shifting to a high-NCM battery market substantially amplifies toxicity-related impacts, with carcinogenic toxicity and freshwater ecotoxicity increasing by 30 % and 25 %, respectively, while the effect on climate change remains lower (∼12 %). This is mainly due to the significantly higher cobalt and nickel intensity of NCM cathodes compared to LFP. Because these metals have higher life-cycle toxicity per unit mass, especially in freshwater ecotoxicity and carcinogenic toxicity, shifting to a high-NCM battery mix leads to a disproportionate increase in those impact categories. Comparable patterns are obtained for the FCV-dominant (S2) and EV-dominant (S3) pathways (Figure S12–S13), and the perturbations do not alter the ranking of the three scenarios. These findings highlight that long-term environmental outcomes are not only sensitive to overall battery deployment volumes, but also to the evolution of battery chemistry composition. The sensitivity analysis confirms that long-term environmental performance depends not only on the scale of electrification but also on the trajectory of battery chemistry, and it pinpoints the assumptions to which the model is most sensitive. In addition, we summarize the overall uncertainty range implied by these tests by constructing an envelope across the tested bounds (Fig. 5b). This envelope illustrates the minimum and maximum percentage changes in cumulative impacts relative to the S1 baseline, providing a concise representation of the plausible long-term range.

4. Discussions and conclusions

Decarbonizing the transportation sector is essential for mitigating climate change and achieving a carbon-neutral society. Both EVs and FCVs are expected to play a significant role in enabling this low-carbon transition. This study critically evaluates the material resource demands and material-related environmental impacts associated with the adoption of EV and FCV technologies. By analyzing three distinct scenarios with varying technological pathways for automotive development, this research provides a comprehensive assessment of the trade-offs between

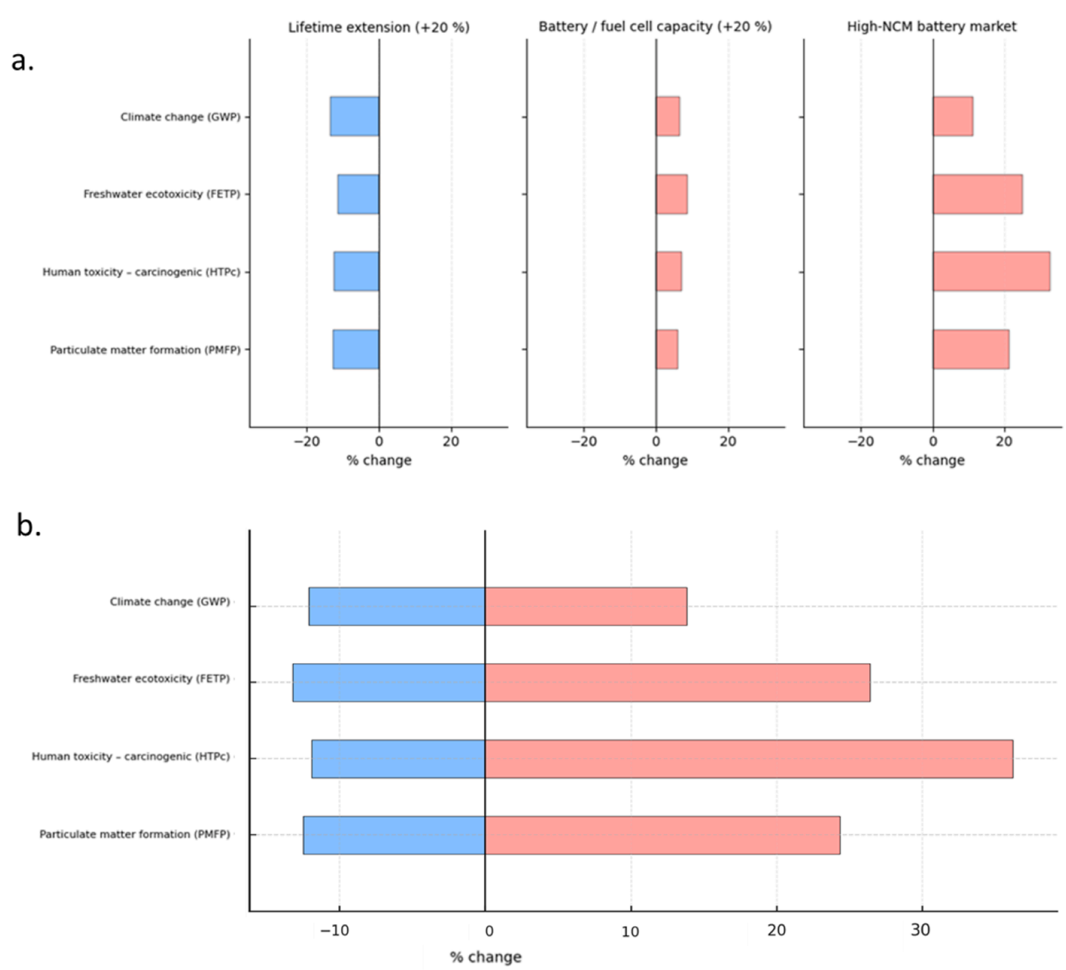

Fig. 5. Sensitivity and uncertainty analysis of cumulative environmental impacts in the balanced S1 scenario. (a) One-at-a-time sensitivity analysis for lifetime, battery capacity/fuel cell power, and high-NCM market share. Results show the percentage change in cumulative impacts relative to the S1 baseline; blue bars indicate reductions, red bars indicate increases. (b) Uncertainty envelope summarizing the minimum and maximum percentage changes across all tested bounds, providing an overall range of projected impacts.

these two technologies in terms of material requirements and associated environmental footprints. In particular, it emphasizes the upstream impacts of material extraction and processing, which are often overlooked but are crucial to understanding the sustainability of EVs and FCVs. These insights contribute to the ongoing debate on the long-term viability and environmental trade-offs of different low-carbon transportation technologies.

4.1. Coordinated EV and FCV development supports a more sustainable transition

This study models three pathways: a baseline (S1), a fuel-cell-vehicle-dominant transition (S2), and an electric-vehicle-dominant transition (S3). Together, these scenarios outline the upper and lower limits of resource use and environmental impact as transportation moves toward decarbonization.. While neither two extreme scenarios is the most likely real-world outcome, these hypothetical cases help to identify key trade-offs in long-term policy planning. The S3 scenario highlights that EV adoption significantly reduces PGM demand but dramatically increases reliance on battery metals, exacerbating mining-related environmental concerns. The S2 scenario illustrates that hydrogen-based FCVs reduce battery demand but introduce new sustainability challenges due to PGM-intensive fuel cell production. In terms of environmental impacts associated with the generation of these materials, The findings reveal that while each scenario prioritizes different resources, neither eliminates environmental burdens—rather, they shift pollution impacts across different environmental categories. In S3, higher demand for battery metals intensifies GWP and HTPc, while in S2, increased reliance on PGMs exacerbates FETP) and PMFP. The above results further demonstrate that neither a fully battery-electric nor a fully fuel-cell-dominant transition is without sustainability challenges. Instead, a complementary approach that leverages the strengths of both technologies may offer a more reliable pathway to transportation decarbonization (Hydrogen, Scaling Up, 2017; Shin et al., 2019).

While this study focuses on the material production stage, the findings can be interpreted alongside existing full LCAs of electric and fuel cell vehicles. Prior studies show that the total carbon emissions of both technologies vary substantially depending on energy sources, but generally fall within overlapping ranges. Specifically, FCVs exhibit life cycle emissions between approximately 60–70 g CO_2/km when powered by green hydrogen and 120–130 g CO_2/km with hydrogen from steam methane reforming (SMR), varying with hydrogen production methods (Hydrogen, Scaling Up 2017; Haugen et al., 2021). BEVs, on the other hand, range from 65 to 75 g CO_2/km when charged and produced with low-carbon electricity to 115–180 g CO_2/km under fossil-intensive systems (Hydrogen, Scaling Up 2017). These reported ranges reflect heterogeneous assumptions across studies, which explain the variation in absolute values but do not alter the overall conclusion that the life-cycle GHG performance of both technologies depends strongly on the energy source in the use phase. These results suggest that full life cycle GHG emissions alone may not provide a definitive environmental preference between the two technologies. Meanwhile multiple studies and industry trends suggest that FCVs offer notable cost and operational advantages in long-haul and heavy-duty transport applications, primarily due to their higher energy density and shorter refueling times compared to battery electric vehicles (BEVs) (Cullen et al. 2021). In contrast, BEVs are generally more suitable for light-duty vehicles, where their cost, efficiency, and charging requirements align better with usage patterns (Sagaria et al. 2021). These techno-economic considerations have led to increasing support for a differentiated deployment strategy across vehicle segments.

In this context, our analysis adds a complementary system-level dimension by evaluating the upstream material requirements and associated environmental impacts of alternative deployment pathways. The results show that the mixed scenario (S1), where BEVs are prioritized for light-duty vehicles and FCVs for heavy-duty vehicles, not only reflects economic feasibility but also delivers environmental benefits across multiple impact categories, including GWP, FETP, and PMFP. These aligned outcomes suggest that S1 represents a robust and balanced transition pathway even when broader life cycle and cost-related factors are taken into account.

4.2. Material supply risks remain a major challenge

Despite differences in material demand across scenarios, supply risks remain a critical concern for both BEVs and FCVs. Geopolitical concentration, extraction limitations, and market dynamics introduce significant uncertainties regarding the long-term availability of key materials.

The supply chains for critical battery metals like Li, Co, Ni, and Mn face significant risks and vulnerabilities. Co production is highly concentrated, with over half mined in the Democratic Republic of Congo, while China dominates refining(van den Brink et al., 2020). This concentration extends to other metals, with 80–92 % of battery cathode materials passing through China(Cheng et al., 2024). Supply risks exist throughout the entire chain, from mining to manufacturing, with Li and Co identified as the most critical materials(Sun et al., 2019). Disruptions can arise from various factors, including geopolitical tensions, environmental concerns, and social issues like child labor(Althaf and Babbitt, 2021) . To mitigate these risks, measures such as diversifying production, developing new mines and refineries, ensuring sustainable artisanal mining, and promoting recycling(van den Brink et al., 2020).

Although fuel cell PGM demand in the EV-dominated scenario is projected to account for only 4.8 % (the S1 scenario) to 15.7 % (the S3 scenario) of 2020 global PGM production by 2050, supply risks remain a concern due to the geopolitical concentration and volatility of PGM sources. South Africa and Russia collectively account for >80 % of global platinum and palladium production (Li et al., 2023), making the supply chain highly susceptible to disruptions from labor strikes, political instability, and export restrictions(Yuan et al., 2020). Historical events, such as prolonged mining strikes in South Africa and trade sanctions on Russian exports, have already demonstrated the vulnerability of these supply chains(Associated Press, 2014).

To address these risks, key mitigation strategies include diversifying supply chains, expanding mining and refining capacity, implementing responsible sourcing practices, and enhancing material recycling technologies. Developing new mines and refineries can strengthen supply security, while sustainable artisanal and small-scale mining (ASM) initiatives help mitigate social and environmental concerns. Additionally, improving recycling efficiency, establishing closed-loop supply systems, and investing in alternative chemistries are critical for reducing dependence on virgin raw materials and minimizing environmental impacts. Policy frameworks supporting circular economy models, diversified sourcing, and material substitution will be essential for ensuring long-term resource security and a more sustainable transition to low-carbon transportation.

4.3. Real-world constraints to recycling strategies

While our modeling estimates significant recycling potentials, the feasibility of achieving high recycling rates varies substantially across the three scenarios. In the EV-dominant S3 scenario, large volumes of end-of-life batteries generate substantial quantities of recyclable lithium, cobalt, and nickel. This high volume may improve the economic viability of battery recycling and justify investments in dedicated recycling infrastructure(Shafique et al., 2022). However, the diversity of battery chemistries (e.g., NCA, NMC, LFP) may pose challenges for efficient material separation and recovery(Neumann et al., 2022).

In contrast, the FCV-dominant S2 scenario relies heavily on PGMs, which have higher unit economic value and more established refining processes. Despite the high value and recyclability of PGMs, the dispersed nature of end-of-life FCVs and the lack of dedicated collection systems, especially in emerging regions, may constrain practical recovery efforts(Wittstock et al., 2016).

Across all scenarios, barriers such as inefficient collection systems, regional disparities in processing capacity, and limited policy incentives remain key obstacles. Recent regulatory efforts, such as the EU Battery Regulation (Regulation (EU) 2023/1542), provide important benchmarks but are not yet widely adopted (Rizos and Urban, 2024). These observations underscore that while recycling plays a vital role in reducing primary resource demand, its real-world contribution depends strongly on the deployment scenario and supportive policy and technology conditions. Regional disparities in collection systems and processing capacity, particularly between MDCs and LDCs, may further constrain the realisation of recycling potential. Moreover, second-life applications of batteries (e.g. in stationary storage) could delay the timing of recycling flows, limiting the near-term availability of secondary supply. However, due to limited available data, we do not conduct further differentiated calculations in this study.

4.4. Policy implications

From the perspective of upstream material demand and material-related environmental impacts, the analysis confirms that a differentiated deployment across vehicle segments provides a more robust pathway than either extreme scenario. Given the complementary advantages of EVs and FCVs, a segmented approach is appropriate: EVs can be prioritized for LDVs, particularly in urban and suburban areas where charging infrastructure is expanding, as demonstrated by recent developments in the US and China (Davis and Tal, 2021; Schnell et al., 2021). FCVs are more suitable for HDVs, especially in freight and long-distance transport, where longer driving ranges and faster refueling are essential. Several countries, including Japan, South Korea, and Germany, have begun to invest in hydrogen refueling infrastructure to support this transition (Greene and Duleep, 2013).

Sensitivity tests demonstrate that lifetime extension, battery capacity & fuel cell power, and battery chemistry composition are among the most influential parameters shaping long-term material demand, while PGM loading remains critical for FCVs. These findings indicate that demand-side measures can play an important role in reducing future pressures. Durability standards that extend average battery life, continued improvements in energy density to prevent disproportionately larger batteries or stacks, and incentives for a diversified chemistry portfolio, for example by supporting LFP alongside NCM cathodes, are practical measures to address these sensitivities (Rasmussen et al., 2019; Xu et al., 2020). On the FCV side, alignment with existing roadmaps that target substantial reductions in PGM loading by 2030 and beyond is essential to ensure that component-level progress translates into system-level benefits(Wittstock et al., 2016). Supply-side measures remain equally important, including diversification of primary sources, scaling of secondary supply, and strengthened design-for-recyclability and collection standards, in coordination with policies such as the EU Battery Regulation, which already sets specific targets and timelines for implementation (Melin et al., 2021; Rajaeifar et al., 2022).

In summary, these insights provide a more supplementary evaluation of the sustainability implications of EV and FCV transitions, These findings underscore the need for a balanced technological approach, where FCVs and EVs are strategically integrated to minimize extreme resource dependencies and environmental pressures. The insights gained from this scenario-based analysis provide valuable guidance for resource-efficient policy frameworks, material substitution strategies, and investment priorities to ensure a sustainable and resilient transition to low-carbon transportation.

CRediT authorship contribution statement

Zhenyang Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rene Kleijn:** Writing – review & editing, Supervision, Project administration. **Chunbo Zhang:** Writing – review & editing, Validation, Methodology, Data curation. **Hai Xiang Lin:** Writing – review & editing, Supervision, Project administration.

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.

Acknowledgments

Zhenyang Chen would like to thank the support of the China Scholarship Council (No. 201908620087). Hai Xiang Lin expresses his gratitude to the R. Timman Foundation for providing financial support for his work on this research.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108646.

Data availability

Data will be made available on request.

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