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Mining the in-use stock of energy-transition materials for closed-loop e-mobility

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ABSTRACT

The decarbonization of transportation is essential to achieve a carbon neutral planetary society. However, the turn to electromobility is based on advanced technologies (e.g., lithium-ions batteries) that tied our development to many functional materials with problematic supply. In this study, we apply prospective dynamic material flow analysis to explore the potentials for closing material cycles while meeting a full transition to electric for a set of energy-transition materials (ETMs) including lithium, cobalt, nickel, manganese, and natural graphite. Three demand scenarios are applied to develop trajectories for ETM demand, their in-use stock, and derive the potentials to which recycling can substitute for virgin material extraction at the global scale to 2065.

Our results estimate that ETM inflow to use could increase between 20 and 50 times by 2065. However, secondary supply will hardly enable the achievement of circularity in material cycles in the next decades so that the supply of ETMs will remain mainly based on primary material extraction. Nevertheless, from 2040 onwards, recycling volumes could meet up to more than 80% of demand and represent a viable alternative to mining. If the ideal scenario is realized, government policies could have the potential for achieving the dual goal of decarbonizing e-mobility and securing sustainable access to ETMs already in the middle of 2050s. However, the combined commitment and efforts across the value chain of policymakers, companies involved in the cycle, and consumers will be needed to fully realize the great potential for circular economy to work for e-mobility.

1. Introduction

Growing knowledge on the socio-economic metabolism that characterizes the modern society (Baccini and Brunner, 1991; Fischer-Kowalski and Haberl, 1998; Pauliuk and Hertwich, 2015) has improved understanding of the societal value of natural resources (Haberl et al., 2017; Kennedy et al., 2007) in the form of materials and energy to meet essential human needs (Graedel et al., 2015; Haberl et al., 2007; Wiedmann et al., 2015). It has also provided scientific insights in enough detail to discuss resource policy strategies related to human activity (Dewulf et al., 2015; Drielsma et al., 2016; Hatayama and Tahara, 2018; Watari et al., 2021; Liu et al., 2013) and given rise to research efforts related to anthropogenic cycles of resources dominating the technosphere (Clift and Druckman, 2016).

Natural resources marked human development and technology evolution, but past issues and potential risks in their supply (Achzet and Helbig, 2013; European Commission, 2023; Graedel et al., 2015; Hatayama and Tahara, 2018; McCullough and Nassar, 2017) have manifested the fragility of current production and consumption patterns, and ultimately increased apprehension about meeting sustainable demand in the long-term. This fragility amplifies considering the expectations placed in technology to relieve human pressures on Earth' system components such as stratospheric ozone depletion and biodiversity loss, and to achieve a carbon neutral future (Rockström et al., 2009).

More specifically, criticality assessment lists of essential resources comprise most of metals employed in emerging energy systems for low-carbon technology and e-mobility (European Commission, 2023; Graedel et al., 2015). In particular, the envisaged breakthrough to sustainable mobility comes through innovation and lasting technology (e.g.,

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lithium-ions batteries, LIBs) that tied our development to many functional materials with problematic supply such as lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), and natural graphite. Electric vehicles (EVs) are currently in the first phase of a very dynamically growing market, which is expected to drive future demand for metals. The supply of critical materials to enable the transition to electric mobility as well as the demand from competing industrial sectors will intensify the extraction of primary resource (Elshkaki et al., 2018; Mudd, 2020; Vidal et al., 2022) and the footprint of the mining sector (Ciacci et al., 2020; Jowitt et al., 2020; Weng et al., 2016) posing serious challenges to the future sustainability of the global metal supply.

As an alternative to mining, circular flows and recycling loops in material cycles might reduce the dependence on virgin ores through the exploitation of material in-use stocks or urban mines. However, the shift from natural mines to urban mines is often limited by little knowledge about the size of in-use stock and the amount of waste generated at end-of-life (EoL), its location and form in products. This is fundamental information for secondary resource recovery and large-scale recycling. To this goal, mass-balance modelling techniques such as material flow analysis (MFA) aim at quantitative characterization of metal sources, pathways, stocks, and final sinks (Brunner and Rechberger, 2004). MFA has been extensively applied to the anthropogenic cycle of resources relevant to EVs and critical materials (Ciacci et al., 2022; Dunn et al., 2021; Matos et al., 2022; Richa et al., 2014; Slattery et al., 2021; Zeng et al., 2022; Ziemann et al., 2018), increasing understanding of socio-economic metabolism and laying the foundation for predictive models for secondary (i.e., recycled) materials with lower risk of supply shortfalls (Eckelman et al., 2014). However, while electrification of road transport is underway and a significant reduction of internal combustion engine vehicles in favor of hybrid, plug-in, and EVs is expected, the uncertainty of the development and diffusion of new technologies in this sector remain relatively high so as their consequences on material breakdown of vehicles (European Commission, 2020). This requires ongoing trend monitoring in material use and battery market evolution in which resource criticality considerations may play a crucial role.

As part of the Special Issue “Complex Orebodies and Future Global Metal Supply”, this article develops an overarching approach to inform the debate about challenges with future global metal demand and supply. More specifically, a dynamic MFA (dMFA) model is developed to examine whether and to what extent secondary sources of critical and strategic raw materials can substitute for virgin resources extraction, and what contribution recycling can make as part of the circular economy to achieve decarbonization of the global mobility sector to 2065. This work builds upon a set of well-regarded scenarios for EVs, which in turn consider reliable policy, energy and climate setting conditions and trajectories, and it is informed with the current development in battery market technology. Our focus is on global market activity and a longer-term perspective than that of previous studies is adopted as, we believe, only by taking this overarching view of the entire market over an extended period can the full potential of a circular economy for EV batteries be explored. This would allow to better understand the potential future development of the global shares of mining and recycling in total demand, ultimately enabling to discuss how the achievement of decarbonization in the automotive industry could possibly relate with the closure of material cycles for selected energy-transition minerals and metals (ETMs). Li, Co, Ni, Mn, and graphite have been investigated as exemplary ETMs in providing strategic functioning to high-energy density batteries and sustainability in future mobility.

2. Materials and methods

To determine the future potential recycling quantities of the above five ETMs and their contribution to closing material life cycles on a global scale, the growth of in-use stock and annual generation of waste at EoL are estimated as function of global demand inflows and the residence time of products in use till 2065 by means of dMFA. Next, up-to-date recycling methods for selected ETMs are examined to estimate the recovery efficiency potentially achievable at EoL under ideal collection and sorting conditions. This is followed by estimates of recycling potentials for ETMs. Finally, an assessment is given for recycling to contribute to the circular economy and its impact on virgin material extraction.

Our work focuses on light duty vehicles (LDVs) including passenger cars, pick-ups, and light commercial vehicles with pure battery electric propulsion (hereafter, battery electric light duty vehicles, BE-LDVs). Although electromobility also includes trucks, buses, trains, ships, airplanes and e-bikes/scooters, such goods were not considered in this assessment. A detailed description of modelling variables and assumptions is reported in the following paragraphs and the Supplementary Materials.

2.1. Model description

The global annual demand inflows for ETMs have been estimated in seven steps, following summarized. First, the amount of BE-LDVs (vehicles/year) in commerce was projected to 2065 according to three trajectories built upon a set of well-regarded International Energy Agency (IEA) scenarios. Second, the annual global demand for BE-LDVs was broken down by battery type by means of annual market shares. Third, assuming a plausible evolution of the average battery capacity for BE-LDVs, the global sales in number of BE-LDVs has been converted into energy unit (GWh/year) per battery type. Four, estimates of specific energy values (kWh/kg battery) by battery type in the year 2020 were used to estimate battery weight per vehicle (kg battery/vehicle). Fifth, the sales of BE-LDVs by battery type expressed in GWh were multiplied by the specific energy to estimate the total weight of battery type on the market in each year of the analysis. Then, an average chemical composition for battery types was applied to infer the global amount of ETMs contained in BE-LDVs put on market (kg ETM/year by battery type). Finally, the inflow of global demand by ETM (kg ETM/year) was calculated as the sum of individual ETM demand by modelled battery type. The next paragraphs provide a detailed description of the model assumptions and data sources.

2.2. Scenarios of BE-LDV sales

In 2020, the global car population, excluding commercial vehicles, was 1197 million (Statista, 2021a) and, in the period from 1978 to 2020, almost linear growth can be seen (Federal Environmental Agency, 2020). According to the IEA, more than 10 million EVs were on the roads worldwide at the end of 2020. This represents an increase of 43% compared to 2019 and translates into the vehicle in-use stock share of approximately 1%. Overall, about 3 million new electric cars were registered in 2020 (International Energy Agency, 2021a).

Although there is general agreement about the dramatic increase of the EV sector in the coming years, analysts differ on how high the numbers of EVs will be in the future. Global population growth and an associated rise of per capita gross domestic product in the middle class, particularly in emerging and developing economies, are expected to drive EV diffusion (Gapminder, 2021). In addition, developed markets could have stopped manufacturing and selling internal combustion engine (ICE) cars in 10–20 years due to climate change concerns (Harloff, 2021). Analogously, plug-in hybrid EVs are expected to play no longer a role after 2030 and might disappear from the market, mainly because of the cost of offering and maintaining two drive systems in a car is uneconomical for manufacturers and customers (Thielmann and Wietschel, 2020).

The growth supporting incentives could decrease as the competitiveness of EVs increases compared to ICE cars. EVs could then be increasingly subject to taxation, which may contribute to slowing growth. Charging infrastructure and home charging could keep pace with the dynamic development of the battery EV (BEV) market in developed countries. Emerging markets such as India and countries in South America, Asia and Africa could likely to follow the development with only a few years delay, because there is also a buyer class with high purchasing power and many used EVs might find owners in these countries (Bloomberg, 2021).

Increasing alternative mobility concepts such as car sharing and robotaxis, which may enable urban residents to cover their mobility needs without purchasing their own EV, is a trend that may have a slowing effect on the growth rate, but their global diffusion is still relatively negligible to date.

In Bloomberg's calculations, sales of EVs will increase sharply in the next few years to 14 million in 2025 due to policy support, further improvements in battery density and cost, expansion of charging infrastructure. This number of the global fleet of passenger EVs will increase to 54 million by 2025. Globally, that equates to about 16% of passenger car sales in 2025 (BloombergNEF, 2021). In contrast, Deloitte has published a sales forecast for the next decade of the EV market. An annual growth rate of 29% is projected to be achieved by 2030. As a result, total EV sales will likely reach 11.2 million in 2025 and 31.1 million in 2030 (Deloitte, 2020).

Recently, the IEA approached the forecast for EVs with three scenarios, namely the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE). APS and STEPS are exploratory in the sense that they define a set of policies and targets as starting conditions and model possible trajectories for market dynamics and technological progress. APS assumes that all climate commitments by governments are met in full and on time, while STEPS constitute a benchmark for current settings in energy and climate policies. In contrast, NZE is a normative scenario and describes a pathway to achieve net-zero CO_2 emissions by 2050 and keep the temperature rise in 2100 below 1.5 °C. In the STEPS, IEA assumed that 30 million EVs (of which about 25 million BE-LDVs) will be on the road in 2030, while the APS is projected to have 45 million EVs (of which about 36 million BE-LDVs), and NZE 65 million EVs (of which about 55 million BE-LDVs) (International Energy Agency, 2021a).

In our work, for the forecast of the future development of the BE-LDVs and battery market, the IEA scenarios were taken as a basis for prospective MFA. However, since the IEA scenarios estimate the BE-LDV sales to 2030, a logistic growth model was applied to extrapolate plausible trajectories to 2065 (Tables S1 and S2 in the SM), named hereafter respectively as stated policy-oriented scenario (STEPoS), announced pledges-oriented scenario (APoS), and net-zero emissions-oriented scenario (NZEoS). Approaching the year 2065, STEPoS, APoS, and NZEoS assume a saturation of the LDV market with battery EVs.

2.3. Battery types, market breakdown and development

The Li-ion accumulator is the essential battery for EVs. LIBs are characterized by high energy density and usually much better perform than previously used battery types such as lead-acid, Ni-cadmium and Ni-metal hydride. However, there are numerous versions of LIBs, which are characterized by different material breakdown on both the anode and cathode sides, with the latter one having significantly higher variability in composition.

In the automotive industry, the most important requirements for the electrode material are high specific and volumetric energy densities, high safety, high discharge potential and high cycling stability. Currently, the most important cathode types are Li-iron-phosphate (LFP), Ni–Co-aluminum (NCA), and Ni Mn Co (NMC) (Veric, 2020). To date, NMC is the dominant chemistry for LIBs, accounting for about 71% of sales, with NCA following for most of the remainder, while LFP battery chemistry is below 4% for the electric car market (International Energy Agency, 2021a).

The success of NMC cathodes is mainly due to the combo of Ni and Mn. Standard NMC cathode material contains Ni, Co and Mn in equal proportions and is therefore titled 1:1:1, with the number combination reflecting the quantity ratio of these elements. Other common configurations on the market are NMC111, NMC422, NMC523 and NMC622. The lower Co content in newer generations creates a reduction in battery production costs (Veric, 2020). Attempts are being made to reach even higher energy densities usually by introducing more Ni into the NMC cathode material (also known as Ni-rich NMC). The Ni-rich variants are 531, 622, 811 and 955, with five percent Co still present in an NMC955 cathode (Competence Network Li-Ion Batteries, 2021).

LFP cathode exhibits high structural and cyclic stability, resulting in long life and safety. The cathode material is composed of much cheaper materials than those used in NMC and NCA cathodes, which can significantly reduce the production price. It is frequently used in China, where it is used in the Tesla Model 3 and Y. LFP has comparatively lower specific and volumetric energy density than NMC, and it is increasingly used in basic class EVs that have ranges of less than 500 km. NCA is a much more expensive cathode material, but brings many advantages, such as higher capacity and energy density (Veric, 2020).

Data from the relevant literature (Islam et al., 2021; McKinsey, 2018; Statista, 2021b) provide a long-term outlook for LIBs, but usually do not take the most recent LFP trends into account. On the latter point, the two global market leaders in EVs, Tesla and Volkswagen announced in their battery technology roadmaps to use LFP for the small to medium vehicle classes by 2030 (Tesla, 2020; Volkswagen, 2021). In 2021, Tesla's Model 3 is already rolling off the assembly line in Shanghai with LFP batteries from CATL, and the second largest manufacturer of EV batteries LG Chem plans to produce LFP cells for Tesla in a new production facility starting in 2022 (TeslaMag, 2021).

The Nickel Institute points to the competitive advantage of LFP compared to NMC. For example, the LFP cathode is said to be 43% cheaper and about twice as durable (4000 cycles instead of 2000 cycles). The safety of LFP can also be ranked higher. This is due to the lower energy density (140 instead of 200 Wh/kg) (Nickel Institute, 2020). Thus, an LFP battery is at a clear disadvantage in terms of weight and range compared to NMC. Therefore, NMC will be likely used for all premium and upper mid-range EVs. Nevertheless, LFP batteries could be the first choice as a traction system for the still developing mass market of affordable small and compact cars and make EVs in the price range of 20–25k€ (without subsidies) possible by 2030. The current market development already shows a strong trend towards LFP batteries (GlobalSpec, 2022). This is factored into the calculation of the quantities of ETMs required, as LFP do not use materials such as Co and Mn and may be permanently implemented in lower segments of the vehicle classes.

Based on information by some stakeholders of the EVs sector (GlobalSpec, 2022; Nickel Institute, 2020; Tesla, 2020; TeslaMag, 2021; Volkswagen, 2021), a market share trajectory is proposed for the model calculations to forecast the future market development for battery chemistries including LFP, NMC955, NMC811, NMC622, NMC111, and NCA. Specifically, LFP will steadily gain market share through 2035 as affordable small cars and midrange wagons with LFP gain market share. Only low-cobalt NMC such as NMC811 and increasingly "high nickel" NMC955 will be used by 2035. NMC111 will no longer be on the market by 2030. NCA and lithium-manganese-oxides will continuously lose market share and disappear from the market by 2035. From 2035 on, the determined values of the market shares of the battery types are carried forward in their tendency, because a forecast for the time after that must be inaccurate. Nevertheless, it is important to find out whether the known battery types satisfy the demand for critical raw materials also for the global market development of EVs until 2065. (Tables S3–S5 in the Supplementary Material A and Fig. S1 in Supplementary Material B).

2.4. ETM demand

The main battery types identified and projected to 2065 are then linked to material requirements for quantification of ETMs employed in battery manufacturing. In our model it is assumed that the average battery capacity linearly increases over time from 48 kWh/vehicles in 2015 to 83 kWh/vehicle in 2050 due to technological progress (Knehr et al., 2022; Research Interfaces, 2021), and that stabilizes hereafter. Annual values of average battery capacities are then used to convert the global sales in number of BE-LDVs into energy unit (GWh/year) per battery type. Specific energy values for LFP, NMC955, NMC811, NMC622, NMC111, and NCA for the year 2020 (Xu et al., 2020) are prorated by annual average battery capacity to estimate the evolution of specific energy values by battery chemistry.

Total mass batteries by chemistry type to 2065 was then calculated by dividing the total battery capacity for each battery type by specific energy values of NMC955, NMC811, NMC622, NMC111, NCA, and then linked to ETM requirements for mass quantification. An average ETM composition per battery type (Table S6 in Supplementary Material A) was inferred from the relevant literature (Castelvecchi, 2021; International Energy Agency, 2021b; Islam et al., 2021; Dunn et al., 2021) and used to estimate the requirement for ETM in each battery chemistry (kg ETM/kg battery). Table 1 lists the average composition by battery type used in our analysis.

Lastly, the inflow of global demand by ETM (kg ETM/year) was calculated for each battery type by multiplying the annual amount of LFP, NMC955, NMC811, NMC622, NMC111, and NCA on the market by the related average composition reported in Table 1. Individual ETM demand by modelled battery type were then summed up to provide the cumulative inflow of global demand for ETMs used in the dMFA model.

2.5. Generation of ETMs at end-of-life and recycling

The raw materials in a LIB can go through a cycle that can be closed via recycling. To determine when and how many EV batteries are available for recycling in each year to 2065, we used a delayed dMFA model with lifetime distribution functions (i.e., normal distribution) to model the probability to become waste. The average duration of first use LIBs is 12 years (Geotab, 2022). However, we have evaluated the robustness of our results by varying in each scenario the lifetime distribution parameters (i.e., mean and standard deviation) as reported in Table 2.

In the calculation of the model, it is assumed that a hypothetical 100% collection rate of EV batteries is achieved. This means that all EV batteries will eventually go to recycling, aligning to the EoL management of lead batteries in the US and Europe (Chen et al., 2019). Current recycling methods and their efficiencies for the recovery of critical materials are considered to the setting of plausible efficiency rates for the model and determine the resulting, theoretical recycling quantities.

The current industrial recycling technologies for EV batteries are pyrometallurgical and hydrometallurgical processing. Experimental data achieve recycling efficiencies up to 99% and above for Li, Ni, Co, Mn for specific methods and source materials and exhibit a pyrometallurgical process for graphite recovery with 91% efficiency (Chen et al., 2019). In a company survey (Bernhart, W., 2019), the mechanical-hydrometallurgical processes are promising processes with recycling rates of 99% for Ni and Co and 90% for Li. The pyrolysis-hydrometallurgical processes are very attractive for Ni and Co with 95% recovery rate. Graphite has not yet been recycled by the companies surveyed. In our model, we set 95% recycling efficiency for Li, Ni, Co, Mn and 90% for graphite (see S4 in the Supplementary Material A and Table S1 in Supplementary Material B).

Table 1
Average composition of battery type by weight assumed in this study (based on Castelvecchi, 2021; International Energy Agency, 2021b; Islam et al., 2021; Dunn et al., 2021).

	[kg/kWh]					
ETM	LFP	NMC955	NMC811	NMC622	NMC111	NCA
Lithium	0.10	0.09	0.10	0.12	0.14	0.10
Nickel	0.00	0.60	0.60	0.53	0.35	0.67
Cobalt	0.00	0.04	0.08	0.18	0.35	0.13
Manganese	0.00	0.03	0.07	0.17	0.33	0.00
Graphite	1.09	0.94	0.96	0.96	0.98	0.98

Table 2
Lifetime distribution parameters for normal distribution used to simulate the residence time in use and waste generation at EoL in the model.

Level	Unit	Mean	Standard deviation
Lower	Year	8	2
Mean	Year	12	3
Upper	Year	16	4

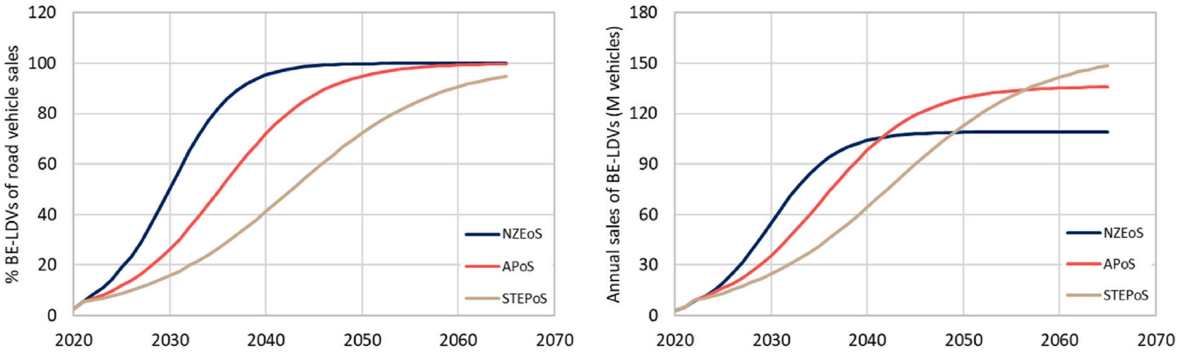
3. Results

3.1. Demand projections

Based on the assumed logistic growth, an S-shape curve results for the sales of BE-LDVs to 2065. Specifically, Fig. 1 (a) shows the annual fraction (percent) of BE-LDVs over total road vehicles for the three scenarios. The forecast estimates an exponential development running towards saturation: the demand curves rise dynamically from 2020 onward, and then growth slows approaching a plateau around the period 2040–2050 for NZEoS, 2050–2055 for APoS, while STEPoS approaches 95% of the market in 2065. Fig. 1 (b) shows instead annual sales of BE-LDVs modelled in the three scenarios, which achieve 109 M vehicles in NZEoS, 136 M vehicles in APoS, and 148 M vehicles in STEPoS in 2065. The necessary battery capacity in 2065 amounts respectively to 9.1 TWh in NZEoS, 11.3 TWh in APoS, and 12.3 TWh in STEPoS.

The global material demand by individual ETMs for BE-LDVs by scenario is explored in Fig. 2 (colored lines). Over the years, the modelled change in battery market shares affects the curves of ETM demands, especially the drop and rise again of Mn demand, due to (i) phase out of Mn rich batteries (drop) and (ii) rising demand again due to ongoing market grow of NMC batteries. In absolute terms, the yearly demand for graphite and, to a less extent, Ni significantly exceeds that for Li, Co and Mn. More specifically, in 2065 global inflows vary between scenarios from 5889 kt/year to 8008 kt/year for graphite, 1924 kt/year to 2325 kt/year for Ni, 555 kt/year to 754 kt/year for Li, 548 kt/year to 745 kt/year for Co, 167 kt/year to 228 kt/year for Mn. The resulting cumulative ETM demands to 192.0–221.0 Mt for graphite, 2065 amount to 63.4–69.1 Mt for Ni, 18.2–19.7 Mt for Li, 18.2–20.0 Mt for Co, and 5.9–6.8 Mt for Mn.

Although different modelling assumptions and different time perspectives do not always enable for univocal comparison between studies, we have attempted to compare our findings with previous estimates in the relevant literature by considering the projected demand of individual ETM from alternative scenarios at the same time of analysis (see Table S2 in the Supplementary Material B). Overall, the long-term perspective adopted in this study and the explored scenario storylines describe possible trajectories that would require relatively medium to low amounts of critical and strategical resources, especially cathode materials, compared to demand ranges estimated for 2040 and 2050 in (Dunn et al., 2021; Xu et al., 2020). These findings seem, hence, to be supportive of the envisaged decarbonization in mobility at lower ETM consumption levels, with relevant consequences for ETM supply as we discuss in the following paragraphs. It is worth highlighting, though, that the evolution of battery chemistry plays a fundamental role in determining the level of individual ETM demand, so that technological progress in battery manufacturing should be carefully evaluated in future advancements, possibly incorporating criticality considerations into material selections and product design.



(a)

(b)

Fig. 1. (a) Percent BE-LDVs of road vehicle sales by scenario. (b) Annual sales of BE-LDVs in million (M) vehicles by scenario.

3.2. The potential for secondary supply

Black lines in Fig. 2 depict the projected amount of ETMs generated at EoL as dictated by the assumed average lifetime of 12 years (solid lines) and visualize the time delay that may occur from extending the average battery lifetime from 8 to 16 years (dotted lines), respectively. Table 3 reports annual outflow from use for individual ETM and scenarios for some selected years.

Fig. 3 shows the results of our scenario calculations about how far recycling can contribute to raw material availability, with the example of Li as it is representative for the ETMs here investigated. On the primary y-axis axis, the required ETM amounts for the annual battery production are plotted in a stacked bar chart, which is composed of the necessary amounts from mining (blue bars) and those potentially supplied from recycling (orange bars), with the latter being calculated by multiplying the average amount of ETM outflows by the theoretical recycling efficiency rates assumed in the model (Tables S7–S21 in the Supplementary Material A and Figs. S2–S6 in the Supplementary Material B).

On the secondary y-axis, the achievable old scrap supply ratio (OSS) of each year can be read off in percentage for the three scenarios. OSS measures the fraction of old scrap over the total demand for a given material, ultimately providing an indication of the achievable degree of material circularity (Ciacci et al., 2020). The results show that until 2040, secondary supply could not be able to make a significant contribution to meeting demand, with all the scenarios approaching 30% OSS. After that, the dynamics of each scenario determine specific OSS results, with NZEoS achieving higher OSS scores at a faster pace than APoS and STEPoS.

OSS for Li experiences a strong growth in the next 10 years and could have about half of the demand met by secondary supply around 2050 in STEPoS, 60% in APoS e already approaching ideal circularity in NZEoS. After another 15 years, the recycled share could be higher than 80% in all the scenarios, so that, ideally, an almost-circular Li anthropogenic cycle can be established. Assuming that the available Li at EoL undergoes closed-loop recycling, the mining peak could be reached in the early 40's, and mining volume might then decrease steadily. Ni, Co, and graphite follow almost the same pattern as for Li. The peak of the mining volume is also in the same period.

Instead, Mn shows a somewhat different course: a first peak that locates around 2026, then primary supply drops before a second peak occurs around 2045. The reason for these trends is that in the present model the Mn-rich battery NMC111 expires in 2030 and causes the drop in the total demand, with the lack of Mn-rich EV batteries gradually becoming unavailable for recycling. In correspondence of the drop in primary material supply noticeable in Fig. 3, OSS clearly peaks driven by higher fraction of secondary supply to meet demand.

Despite discrepancies resulting from market dynamics for battery chemistry, our model indicates that, in principle, for Li, Ni, Co and Mn secondary supply could meet a substantial fraction of the demand, laying the basis for creating a nearly complete circular economy over the next 30–40 years if recovery and recycling practices are successfully implemented at EoL. This means that, in theory, the ETMs yearly required for production can come to 80% from recycling and comparatively small quantities would have to be additionally mined.

3.3. ETMs' in-use stock vs natural reserve

Table 4 reports global in-use stocks of ETM by scenario in selected years. Overall, the greatest net-addition to the in-use stock is estimated to occur around the year 2036 for NZEoS, in 2041 for APoS, and in 2049 for STEPoS, in correspondence of which annual ETM accumulation peaks and then decline off due to the achievement of steady-like state.

If the estimated demand can count on a reliable material supply from secondary sources as dictated by the useful lifetime and by an almost ideal recycling, we have estimated the progressive reduction of the extraction of virgin reserves for ETMs attributable to e-mobility only. That is, starting from the known reserves at today levels (Table S22 in the Supplementary Material A), the annual extraction necessary to satisfy the demand for ETMs was estimated as the complement to secondary supply. Such a comparison is merely speculative as it does not include the potential demand increase coming from other sectors, which are in many cases predominant today in terms of market shares compared to e-mobility such as steelmaking and superalloys for Ni, Co, Mn and refractories for graphite, nor future expansion of orebodies extraction (Jowitt et al., 2020) or inefficiency at mining and processing stages (Nassar et al., 2022). In accordance with Mudd, reserves constitute an underestimation of the true global reserves and therefore of the ultimately recoverable resources, the measurement of which is essential to support humanity in meeting its needs and inform the long-term availability of natural stocks of metals and minerals (Mudd, 2021). However, a detailed and accurate estimate of reserves and resources is beyond the scope of this study. Our intention is to provide a quantitative comparison between natural and anthropogenic reserves, providing for the latter a reliable estimate of the recyclable potential that could decrease the dependence on primary supply, if recycling is adequately exploited.

Despite this partial view, our model estimates that the accumulation of ETMs in the in-use stock may approach about 10% of the total (natural plus anthropogenic) reserve of Li (9.7% ± 0.2%), Ni (9.7% ± 0.1%), and graphite (11.2% ± 0.2%) in 2065 up to 33.5% (± 0.4%) of Co. Mn anthropogenic stock would be instead negligible (only 0.2% ± 0.0% of total reserve). At the stationary conditions assumed in 2065, the anthropogenic reserve of ETMs would be equivalent to about 12 years of inflow to use at the global level. It is therefore evident that the urban mine of ETMs can be an important source in the procurement of strategic

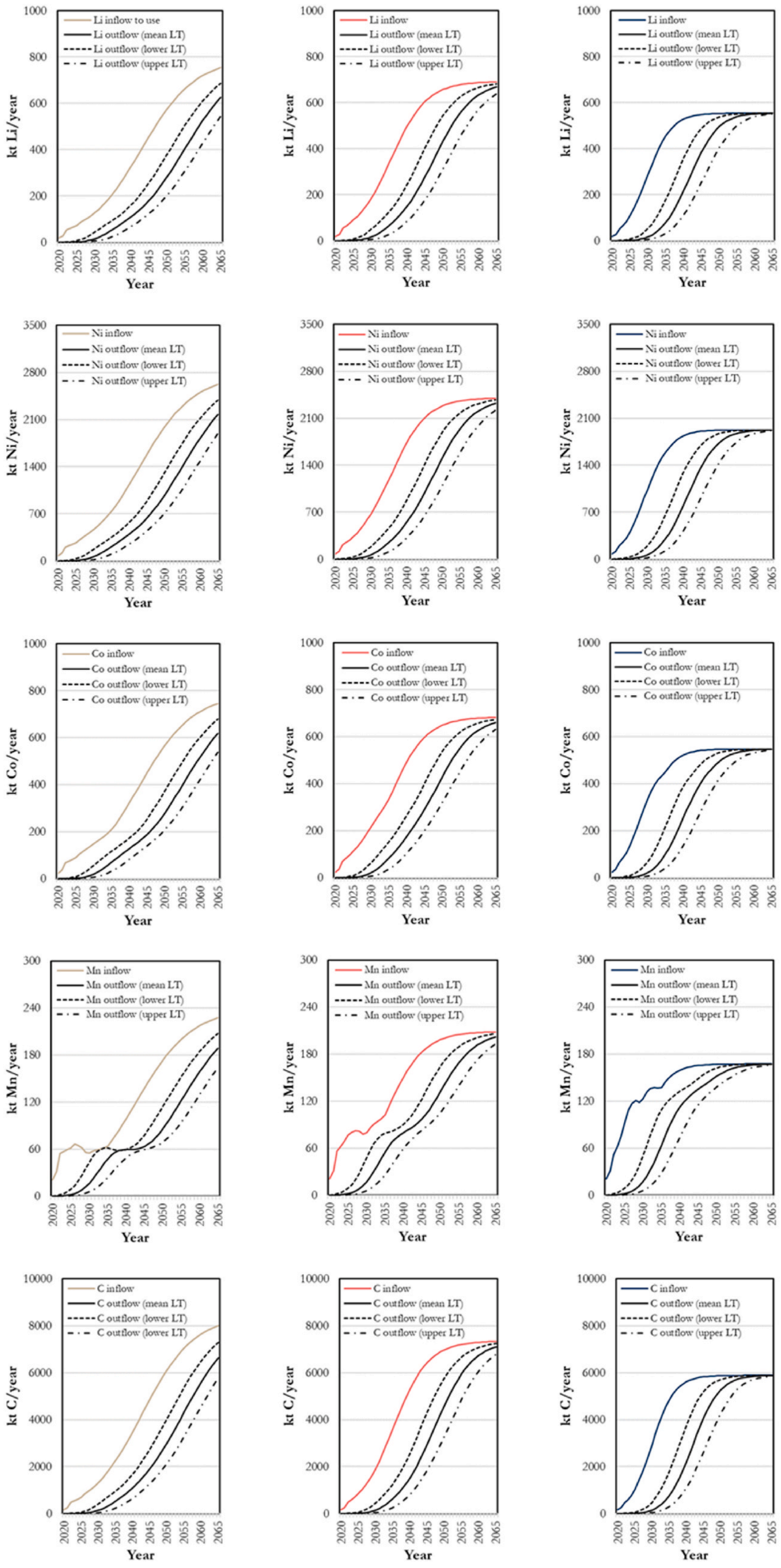


Fig. 2. Global material demand by individual ETMs and scenario (colored lines). Black solid lines represent the projected amount of ETMs generated at EoL by assuming an average lifetime (i.e., "mean LT") of 12 years. Black dotted lines visualize the amount of ETMs generated at EoL by changing the average battery lifetime at 8 and 16 years.

Table 3
Annual outflow from use for individual ETM by scenario in selected years. Values in kt/year.

Scenario	ETM	2030	2035	2040	2045	2050	2055	2060	2065
STEPoS	Li	1,55E+01	5,62E+01	1,09E+02	1,80E+02	2,82E+02	4,04E+02	5,26E+02	6,26E+02
	Ni	6,29E+01	2,12E+02	3,97E+02	6,38E+02	9,81E+02	1,41E+03	1,83E+03	2,17E+03
	Co	2,04E+01	7,07E+01	1,28E+02	1,89E+02	2,80E+02	4,00E+02	5,19E+02	6,18E+02
	Mn	1,66E+01	4,76E+01	5,96E+01	6,35E+01	8,60E+01	1,22E+02	1,59E+02	1,89E+02
	C	1,37E+02	5,26E+02	1,10E+03	1,89E+03	2,99E+03	4,30E+03	5,58E+03	6,64E+03
APoS	Li	1,63E+01	6,65E+01	1,51E+02	2,79E+02	4,33E+02	5,60E+02	6,34E+02	6,69E+02
	Ni	6,60E+01	2,50E+02	5,49E+02	9,87E+02	1,51E+03	1,94E+03	2,20E+03	2,32E+03
	Co	2,14E+01	8,34E+01	1,76E+02	2,92E+02	4,30E+02	5,53E+02	6,27E+02	6,61E+02
	Mn	1,73E+01	5,51E+01	7,99E+01	9,73E+01	1,32E+02	1,69E+02	1,91E+02	2,02E+02
	C	1,44E+02	6,26E+02	1,52E+03	2,93E+03	4,59E+03	5,94E+03	6,73E+03	7,10E+03
NZEoS	Li	1,66E+01	8,00E+01	2,17E+02	3,84E+02	4,96E+02	5,39E+02	5,51E+02	5,54E+02
	Ni	6,71E+01	2,99E+02	7,89E+02	1,36E+03	1,73E+03	1,87E+03	1,91E+03	1,92E+03
	Co	2,18E+01	9,98E+01	2,53E+02	4,03E+02	4,92E+02	5,33E+02	5,44E+02	5,47E+02
	Mn	1,75E+01	6,38E+01	1,12E+02	1,35E+02	1,52E+02	1,63E+02	1,66E+02	1,67E+02
	C	1,48E+02	7,58E+02	2,20E+03	4,03E+03	5,26E+03	5,72E+03	5,85E+03	5,88E+03

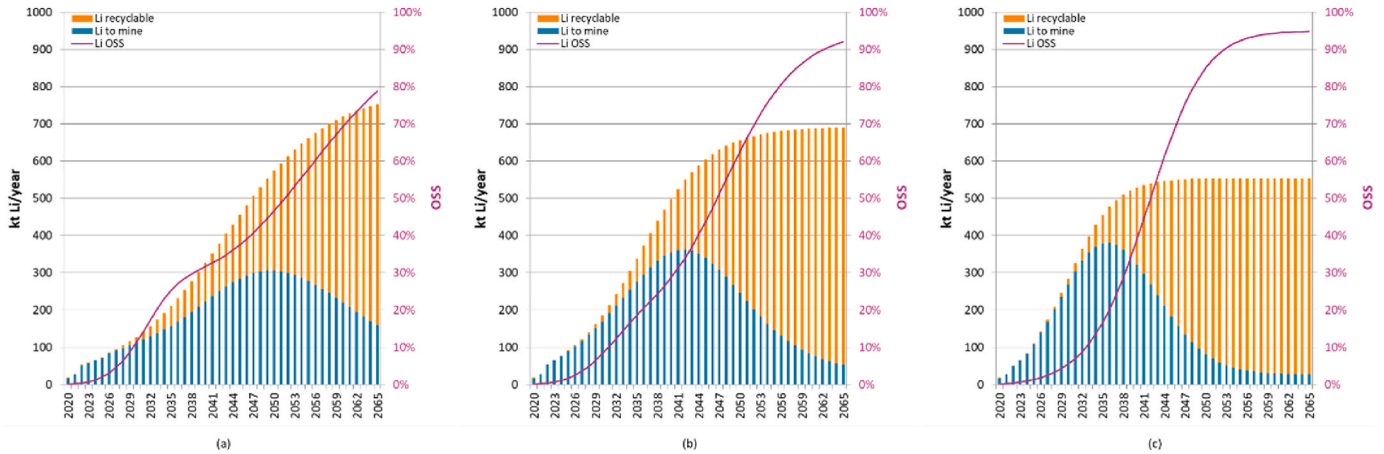


Fig. 3. The required lithium amount from mining (blue bars) and those potentially supplied from recycling (orange bars) estimated for STEPoS (a), APoS (b), and NZEoS (c). Old scrap supply ratio (OSS) for 2020–2065 is plotted on the second y-axis.

Table 4
Global in-use stock of ETM by scenario for selected years. Values in kt/year.

Scenario	ETM	2030	2035	2040	2045	2050	2055	2060	2065
STEPoS	Li	8.20E+02	1.51E+03	2.46E+03	3.74E+03	5.19E+03	6.57E+03	7.67E+03	8.44E+03
	Ni	3.05E+03	5.43E+03	8.67E+03	1.30E+04	1.80E+04	2.28E+04	2.67E+04	2.93E+04
	Co	1.01E+03	1.69E+03	2.54E+03	3.72E+03	5.13E+03	6.49E+03	7.58E+03	8.34E+03
	Mn	5.78E+02	7.04E+02	8.40E+02	1.15E+03	1.57E+03	1.98E+03	2.32E+03	2.55E+03
	C	7.94E+03	1.54E+04	2.60E+04	3.97E+04	5.51E+04	6.97E+04	8.15E+04	8.97E+04
APoS	Li	1.04E+03	2.20E+03	3.81E+03	5.53E+03	6.87E+03	7.67E+03	8.05E+03	8.21E+03
	Ni	3.85E+03	7.89E+03	1.34E+04	1.93E+04	2.39E+04	2.66E+04	2.80E+04	2.85E+04
	Co	1.28E+03	2.44E+03	3.91E+03	5.50E+03	6.79E+03	7.58E+03	7.95E+03	8.11E+03
	Mn	7.09E+02	9.84E+02	1.28E+03	1.69E+03	2.08E+03	2.31E+03	2.43E+03	2.48E+03
	C	1.01E+04	2.26E+04	4.02E+04	5.87E+04	7.30E+04	8.14E+04	8.55E+04	8.72E+04
NZEoS	Li	1.40E+03	3.13E+03	4.87E+03	6.00E+03	6.47E+03	6.61E+03	6.64E+03	6.65E+03
	Ni	5.17E+03	1.12E+04	1.72E+04	2.09E+04	2.25E+04	2.30E+04	2.31E+04	2.31E+04
	Co	1.71E+03	3.47E+03	5.03E+03	5.97E+03	6.39E+03	6.53E+03	6.57E+03	6.57E+03
	Mn	9.12E+02	1.38E+03	1.66E+03	1.85E+03	1.95E+03	2.00E+03	2.01E+03	2.01E+03
	C	1.37E+04	3.22E+04	5.13E+04	6.36E+04	6.87E+04	7.02E+04	7.06E+04	7.07E+04

resources for the decarbonization of mobility and the implementation of the circular economy, as we discuss in the next section.

4. Discussion

In principle, material circularity models with high recycling rates decouple value creation from raw material consumption and improve the economic (Drabik and Rizos, 2018) and environmental (Beaudet et al., 2020) performance of e-mobility, ultimately achieving a better environment and society (Abdelbaky et al., 2021). It is evident from this work that future development and successful implementation of closed-loop recycling in the EV battery cycle on a global scale can succeed and provide great added value to society in the form of secured, sustainable, and more distributed worldwide access to ETMs compared to a supply based on virgin ores and deposits.

However, our model also clearly shows that secondary sources will hardly enable the achievement of circularity in material cycles in the short term, at least for the set of elements investigated here. Based on our results, the global demand for ETMs might increase between × 25 and ×33 for Li, ×20 and ×27 for Ni, ×18 and ×24 for Co, × 6 and × 9 for Mn, ×31 and ×41 for graphite by 2045 compared to 2020 levels, with further growth respectively at ×30 and ×41 for Li, × 25 and × 33 for Ni, ×22 and ×30 for Co, ×8 and ×11 for Mn, ×38 and × 51 for graphite by 2065. It should be noted that about half of the cumulative demand for ETMs necessary by 2065 will have to be mined before they can be found in feedback loops: given that strategical ETMs such as Ni, Co, and Li are used in large quantities in demand-competing sectors (Zeng et al., 2022) such as the steel industry, stationary energy storage and consumer electronics, the cumulative material demand for BE-LDVs batteries alone is an indication that electromobility may be problematic without intensive recycling and that ETM supply would remain mainly based on primary extraction in the next 15–20 years.

The business opportunities for the mining industry are hence significant considering the resulting growth in the market potential over the next few decades. However, this could be likely associated with a massive expansion of existing mines, exploration, and commissioning of new sites, which might further increase the pressure on the mining industry to work on its transparency regarding environmental, social, and governmental (ESG) requirements (Lèbre et al., 2022), associated risks, and stakeholders' response (Aaen et al., 2021; Jowitt et al., 2020; Luckeneder et al., 2021; Walter and Wagner, 2021).

For instance, stakeholders in the automotive and battery economy have started to claim for responsible and sustainable corporate behavior through global supply chain (Standard Ethics, 2022) and additional demand for transparent, complete ESG reporting and assessment comes from the legislation (European Commission, 2022), and investors who increasingly want to invest in a responsible and environmentally friendly way. In this context, the mining industry could see the dynamic development of ETM demands as an opportunity, with the market potential only being fully leveraged if the durations of exploration, authorization, site development, operation and closing are adjusted accordingly.

Analogously, consumers may have active role in influencing mineral extractors and automakers for adopting sustainable sourcing and transparent supply chains. But a lack of awareness among consumers about the impacts of ETMs supply and the environmental costs of energy transition, other than global warming, risks to distort the role of consumers in demanding for sustainable material sourcing (Liu et al., 2022) and the establishment of ETMs demand-reducing strategies such as car-sharing models or service-oriented schemes as cultural attitudes and social status remain primary motivations in the purchase of vehicles (C&EN, 2022; Liao et al., 2017).

These aspects highlight the importance of government policies in determining the achievement of sustainability in the future supply of ETMs. Even if our scenarios model different socio-economic trajectories, which ultimately explain the differences in their results, they all assume that as soon as significant volumes of recycling may contribute to demand, sustainable ETM sourcing through recycling could be a viable alternative to mining further down the line. If ideal recycling is into practice, from 2040 onwards recyclable volumes could progressively increase and lead mining to peak and then decline off. As depicted in Fig. 3, the mining industry can expect a reduction in extraction needs in the late twenties, early thirties from returns of batteries that could be recycled. It would take another 25 years, with a continuous increase in recycling volumes, before a nearly complete circular economy could have emerged. Once a circular economy has been achieved, the relatively long timeframe until 2065 in our study models that primary supply can stabilize at least as high or up to 2 times the current levels in all the scenarios considered. Eventually, the mining industry may decide to enter the recycling business itself to take advantage of this transformation at the latest as soon as the demand for secondary material comes into the order of magnitude of the primary material. If the NZEoS is realized, government policies could have the potential for achieving the dual goal of decarbonizing e-mobility and securing sustainable access to ETMs already in the middle of 2050s.

The extent to which recycling will reduce pressure on natural mines depends on our capability to intercept and re-enter "urban mines" in the cycle. In fact, although theoretical OSS results individuate up to 80–90% potential for secondary supply to meet the future demand, the current management of EVs batteries and ETMs recovery is affected by significant inefficiencies during waste collection, sorting, and separation stages (Dunn et al., 2021). In addition, once the performance of LIB has dropped to about 80–70%, the battery can be used as energy storage in homes and power grids (i.e., second use) for another few years before being collected and recovered (Di Persio et al., 2020). In contrast, recycling processing efficiencies are relatively high, even in the case of graphite, so that theoretical OSS estimates may be turn into actual recycled contents with relative efforts under improved waste management conditions. To this aim, enabling material recovery through design approaches that may support the retention of value at EoL such as design for disassembly (DfD) will boost secondary supply, particularly if framed under strategies for resource efficiency such as extended producer responsibility (EPR) (Babbitt et al., 2021).

However, the successful implementation of strategies and approaches aimed at the retention of value at EoL and material recovery might be hindered by the current structure of the global automotive industry. The automotive network is highly fragmented worldwide, with upstream geography of material supply being very often separate from battery production and assembly, and ultimately swinging between globalization trends to reduce costs versus propulsion to regionalize and localize supply chains. Furthermore, the underlying patterns of raw materials extraction differ from those of manufacture, use and EoL management so that the successful implementation of overarching tools such as EPR or DfD is often prevented to date. Therefore, the effort of implementing design solutions cannot remain isolated, but it must be adequately supported by incentives, regulation, and directives. Such a system vision would facilitate industrial partnership and vertical integration between upstream (i.e., the mining industry) and downstream (i.e., the recycling industry) actors towards circular business models (Bridge and Faigen, 2022).

Overarching approaches combining commitment and efforts of policymakers, industry, and consumers may hence increase the resilience of secondary supply securement in e-mobility, also considering possible changes in the current value chains. In recent years, there has been a sharp increase in investment in technology developers and battery manufacturers (Holland and Edmondson, 2021) to improve the production efficiency of LIBs and maximize their capacity. Further variations may occur in the development of battery types and their raw material requirements. For example, LFP batteries may take a larger share or other battery types such as solid-state batteries may enter the market. These advances might inevitably affect the current ETMs' value chain and further question the effectiveness of long-term circular solutions unless a life cycle thinking perspective is fully established in the current management and use of resources.

5. Conclusions

The decarbonization of the mobility sector is a vital part of the strategies to achieve global net-zero emission of CO_2 by 2050. However, the shift to electromobility is constrained by advanced technologies such as LIBs that could increase demand for ETMs by 20–40 times compared to 2020 levels. In these demand scenarios, the mining industry is challenged to meet an intensive procurement of materials while improving its ESG results as primary resource extraction is likely to remain dominant in ETMs' supply. As shown by our model, from 2040 secondary sources could become progressively significant and timely for sustainable access to resources, laying the foundation for fully realizing the great potential for circular economy for EV batteries. However, design solutions and improving the efficiency of material recovery at EoL are key means of creating an efficient and resilient value chain, transforming the potentially recyclable material fraction into actual recycled streams, if these efforts are adequately supported by governance and regulation.

Although the automotive sector has captured most of the attention, electrification is expected to spread to all transportation modes. For instance, electric bikes and boards are growing from niche uses to high penetration rates in the personal mobility markets. Similarly, innovative hybrid electric propulsion systems are explored in the aerospace industry (Airbus, 2016). The breakthrough in sustainable mobility made possible by innovations is transversal to all transport segments and requires lasting technological change to face the envisaged societal challenges. Guaranteeing access to resources such as those covered in this work is essential to promote sustainability in future mobility and, by extension, to drive sustainable development.

Author statement

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Declaration of competing interest

None

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2023.104155.

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