Advances in Applied Energy 9 (2023) 100116

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen

Critical metal requirement for clean energy transition: A quantitative review on the case of transportation electrification

Chunbo Zhang[a], Jinyue Yan[b,c,*], Fengqi You[a,*]

[a] Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY 14853, United States
[b] Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong
[c] Future energy center, Mälardalen University, Västerås 72123, Sweden

ARTICLE INFO

Keywords:
Battery
Fuel cell
Electric vehicles
Material flow analysis
Metal

ABSTRACT

The clean energy transition plays an essential role in achieving climate mitigation targets. As for the transportation sector, battery and fuel cell electric vehicles (EVs) have emerged as a key solution to reduce greenhouse gasses from transportation emissions. However, the rapid uptake of EVs has triggered potential supply risks of critical metals (e.g., lithium, nickel, cobalt, platinum group metals (PGMs), etc.) used in the production of lithium-ion batteries and fuel cells. Material flow analysis (MFA) has been widely applied to assess the demand for critical metals used in transportation electrification on various spatiotemporal scales. This paper presents a quantitative review and analysis of 78 MFA research articles on the critical metal requirement of transportation electrification. We analyzed the characteristics of the selected studies regarding their geographical and temporal scopes, transportation sectors, EV categories, battery technologies, materials, and modeling approaches. Based on the global forecasts in those studies, we compared the annual and cumulative global requirements of the four metals that received the most attention: lithium, nickel, cobalt, and PGMs. Although major uncertainties exist, most studies indicate that the annual demand for these four metals will continue to increase and far exceed their production capacities in 2021. Global reserves of these metals may meet their cumulative demand in the short-term (2020–2030) and medium-term (2020–2050) but are insufficient for the long-term (2020–2100) needs. Then, we summarized the proposed policy implications in these studies. Finally, we discuss the main findings from the four aspects: environmental and social implications of deploying electric vehicles, whether or not to electrify heavy-duty vehicles, opportunities and challenges in recycling, and future research direction.

1. Introduction

Modern society is accelerating the transition to a clean energy system worldwide [1]. An increasing number of countries, industrial sectors, and enterprises are striving to reduce their greenhouse gas (GHG) emissions to the "net zero", which requires the large-scale deployment of a variety of clean energy technologies such as electric vehicles (EVs), photovoltaic panels, and wind turbines [2]. Transportation is identified as one of the key sectors for achieving decarbonization goals [3]. CO_2 emissions from road transportation accounted for 78% of the total global transportation CO_2 emissions in 2020 [4]. The operation of internal combustion engine vehicles (ICEVs) is a major source of unsustainable energy consumption owing to almost exclusive reliance on liquid fossil fuels [5]. Alternative fuels such as electricity, hydrogen, and biofuels have been recognized as having the potential to mitigate GHG emissions [6]. Advances in battery and fuel cell technologies have made alternative fuel vehicles such as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) promising strategies to decarbonize the transportation sector [7,8]. In 2021, investments in the electrification of the transportation sector accounted for 36% of total global clean energy transition investments [9]. In turn, the ongoing clean energy transition significantly relies on critical metals. Critical metals are those with high technological vitality to the functionality of various emerging technologies but may suffer a potential supply risk [10]. Critical metals such as copper, lithium, nickel, cobalt, platinum group metals (PGMs), and rare earth elements (REEs) are essential components in today's EV tech-

Abbreviations: BEV, Battery electric vehicle; CCUS, Carbon capture, utilization, and storage; COP26, 2021 United Nations Climate Change Conference; EREV, Extended range electric vehicle; EoL, End-of-life; EV, Electric vehicle; FCEV, Fuel cell electric vehicles; HDCV, Heavy-duty commercial vehicle; HDPV, Heavy-duty passenger vehicle; HEV, Hybrid electric vehicle; GHG, Greenhouse gas; ICEV, Internal combustion engine vehicle; IEA, International Energy Agency; LCO, Lithium cobalt oxide; LDCV, Light-duty commercial vehicle; LDPV, Light-duty passenger vehicle; LFP, Lithium iron phosphate; LIB, Lithium-ion battery; Li-air, Lithium-air; Li-S, Lithium-sulfur.

* Corresponding authors.
E-mail address: fengqi.you@cornell.edu (F. You).

https://doi.org/10.1016/j.adapen.2022.100116
Received 10 November 2022; Received in revised form 30 November 2022; Accepted 4 December 2022
Available online 6 December 2022

nologies [11]. There are concerns about the supply risks of those metals due to the rapid growth of transportation electrification and mobilization [12]. International Energy Agency (IEA) estimates that the primary demand (total demand net of recycled volume) of copper, lithium, and cobalt will far exceed their committed mine production in 2030 [11].

Material flow analysis (MFA) is an analytical methodology that models flows and stocks of materials or substances from natural and human activities [13]. MFA has been widely applied to assess the future material requirements for EV batteries and fuel cell systems on different spatial and temporal scales. The objective of this study is to review the recent MFA research on the advances in assessing the critical material requirement for transportation electrification. To achieve this goal, this review is designed to provide insights into the following three important questions:

1 What are the state-of-the-art MFA studies on modeling and assessing EV stocks and flows?
2 What are the projected spatiotemporal dynamic demand characteristics of critical metals for transportation electrification?
3 What are the potential policies to ensure the supply of critical metals for transportation electrification?

Following the introductory section, we present some background and concepts in Section 2, including MFA models, EVs, automobile batteries and fuel cells, and critical metals used in EVs. Section 3 presents the methodology for conducting the review. Section 4 summarizes the characteristics of the studies selected for the review. Section 5 compares the projected annual and cumulative metal demand from these studies. Section 6 categorizes and codes the policies proposed in these studies. We further discuss the main findings in Section 7. Finally, conclusions are drawn in Section 8.

2. Background

2.1. Material flow analysis

MFA is an important method in the toolbox of industrial ecology [14]. The MFA approach is based on the law of conservation of mass and aims to evaluate the metabolism of materials and substances in the anthroposphere [13]. At the same time, MFA is a broad concept, and other studies using methods such as input-output analysis [15,16] and system dynamics [17] to track material flows can also be referred to as MFA studies. From the perspective of industrial ecology, Van der Voet [18] identified three possible approaches to quantify stocks and flows, namely (i) bookkeeping approach that tracks stocks and flows afterward by registering them, (ii) static approach that specifies the linkage between stocks and flows; and (iii) dynamic approach that treats time as a parameter to predict future scenarios. Bookkeeping and static MFA models explore the time scale of a past year or years and, therefore, only offer limited snapshots of past time. They provide information about the anthropogenic metabolism of materials but cannot reveal the dynamics of future resource depletion and waste management [19]. Compared to these two approaches, dynamic MFA is more powerful. After Baccini and Bader [20] developed the first dynamic MFA, it has been widely employed to quantify material cycles and in-use stocks. This enables new perspectives on the patterns and proportions in which materials are used, the impacts that the material stocks have on raw material requirements, waste recycling potential, and associated economic, environmental, and societal profiles [21]. Augiseau and Barles [22] further classified the following modeling approaches of dynamic MFA modeling: (i) retrospective or prospective: depending on whether exploring the past or the future; (ii) flow-driven or stock-driven: depending on whether input flows or stocks drive the model. This paper investigates how MFA has been used to evaluate the material requirement for transportation electrification. Specifically, we examine the spatiotemporal scopes, the modeling approaches, and the objects tracked in those MFA studies.

2.2. Electric vehicles

According to the hybridization ratio of electrification, automobiles can be categorized into six types [23]: ICEVs, hybrid electric vehicles (HEVs), FCEVs, plug-in hybrid electric vehicles (PHEVs), extended range electric vehicles (EREVs), and BEVs. Based on the reports of the IEA [8,12] and the Argonne National Laboratory [24], technical schemas of different passenger cars are depicted in Fig. 1. ICEVs use gasoline or diesel, which combusts inside a combustion chamber. Instead of electrification, adapting biofuels for ICEVs is also a promising way to decarbonize the transportation sector without expanding the use of critical metals [25]. BEVs (Fig. 1a) run fully on electricity stored in a lithium-ion traction battery with an electric motor. Therefore, BEVs are equipped with the highest capacity with batteries than other EVs, as shown in Fig. 2. EREVs (Fig. 1b) and FCEVs (Fig. 1d) also run solely on electric motors but differ in that electricity for EREVs is generated by fossil fuels (i.e., gasoline, and diesel) with an internal combustion engine. In contrast, electricity for FCEVs is generated by hydrogen and oxygen from an inserted fuel cell stack. PHEVs (Fig. 1c) and HEVs (Fig. 1e) are propelled through a combination of an internal combustion engine and an electric motor. BEVs, EREVs, and PHEVs can be charged by connecting to a power grid, while HEVs, FCEVs, and ICEVs typically cannot be charged from external energy sources. Therefore, BEVs, EREVs, and PHEVs not only reduce GHG emissions from transportation but also facilitate meeting peak energy requirements in densely populated urban, reducing strain on the grid and minimizing spikes in electricity costs.

2.3. Vehicle batteries

Battery technology is an essential factor that determines the viability of transportation electrification [7] and has continued to advance over time [26]. There are two types of batteries equipped in a vehicle, a traction battery that power the electric motor of an EV, usually a lithium-ion battery (LIB) pack, and an auxiliary battery pack, such as a lead-acid (Pb-acid) battery that is not employed by electric motors but is charged by the traction battery and used to support all electrical systems [24]. Therefore, traction batteries are required by EVs only, while all vehicles are equipped with an auxiliary battery pack. The Pd-acid battery was the first rechargeable battery invented in 1859, followed by nickel-cadmium (NiCd) batteries invented in 1899 [27]. They have been commonly used to power consumer electronics, as traction batteries for low-speed utility vehicles, and as auxiliary batteries for fossil fuel-powered vehicles. Because of the toxicity of lead and cadmium and their low energy density, Pb-acid and NiCd batteries have been used less after the emergence of new battery technologies [27]. The nickel-metal hydride NiMH formulation was first commercialized in 1989 with the application of a hydrogen-absorbing alloy to replace cadmium and improve its power density [27]. NiMH batteries are used in consumer electronics and HEVs, such as the Ford Escape, Honda Insight, and Toyota Prius [28]. Batteries with higher energy density enable longer travel ranges, and LIBs take the cake regarding high energy density [29,30], as shown in Fig. 3a. In 1991, Sony released the first commercial LIB, and since then, LIBs, such as lithium nickel-manganese-cobalt oxide (NMC), lithium nickel-cobalt-aluminum oxide (NCA), and lithium iron phosphate (LFP) batteries, have gradually become the leading battery technology for EVs [27]. “High-manganese” cathode-based batteries—such as lithium-manganese oxide (LMO) batteries, lithium manganese-nickel oxide (LMNO) batteries, lithium-manganese-iron phosphate (LMFP) batteries—have been developed by using higher share of manganese to substitute other metals that are more subject to supply risk [31,32].

As current LIBs have also reached their limits in energy density [33], developing a sustainable post-LIB industry based on abundant elements is appealing and urgent. Sodium, zinc, calcium, and aluminum-based battery technologies are being developed as alternatives [33]. Moreover, emerging technologies such as metal-anode, anode-free, solid-state electrolytes, and air batteries have been investigated for many years be-

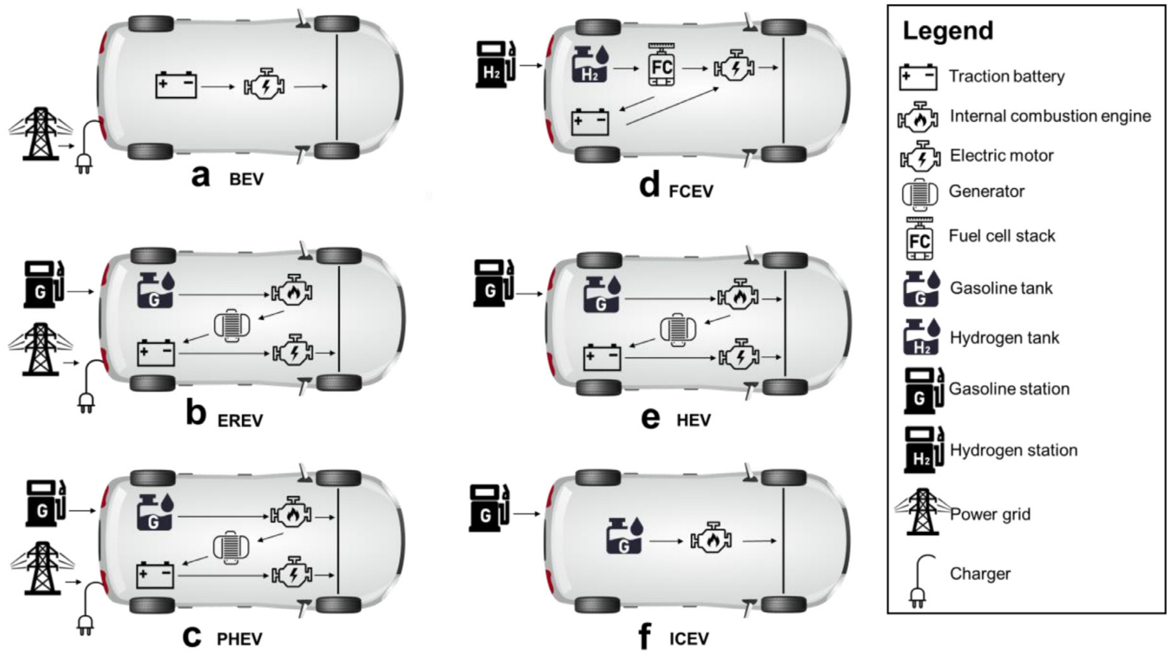

Fig. 1. Technical schemas of vehicles with different powertrains: (a) battery electric vehicle (BEV), (b) extended range electric vehicle (EREV), (c) plug-in hybrid electric vehicle (PHEV), (d) fuel cell electric vehicle (FCEV), (e) hybrid electric vehicle (HEV), and (f) internal combustion engine vehicle (ICEV).

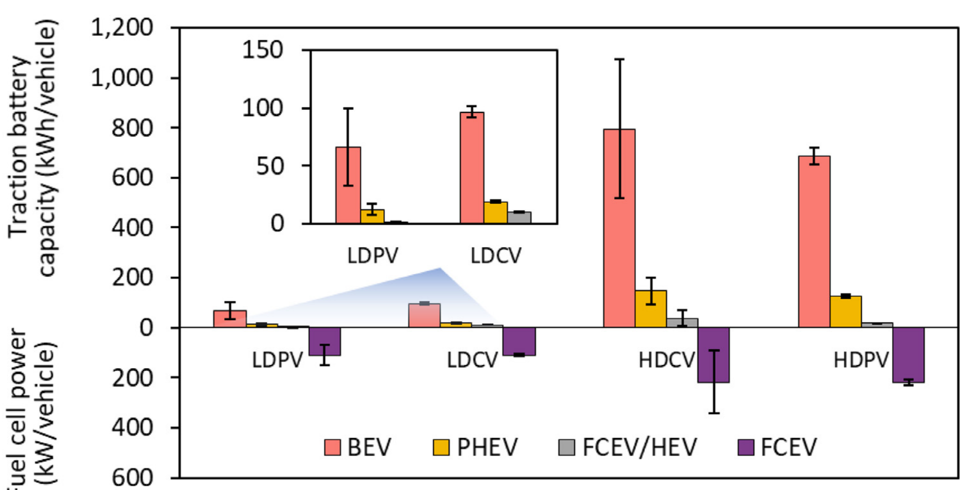

Fig. 2. Average capacity of traction batteries and power of fuel cells of different types of vehicles. LDPV: light-duty passenger vehicle, LDCV: light-duty commercial vehicle, HDPV: heavy-duty passenger vehicle, HDCV: heavy-duty commercial vehicle, BEV: battery electric vehicle, PHEV: plug-in hybrid electric vehicle, FCEV: fuel cell electric vehicle, and HEV: hybrid electric vehicle. The data sources are given in Tables A1 and A2 in the Appendix.

cause of their potential for high theoretical specific energy [7], as shown in Fig. 3b. Most research and development efforts have been focused on lithium-air (Li-air) batteries because they have the highest energy density among other post-LIBs (about 3458 Wh/kg [34]), as shown in Fig. 3b. One of the most prominent drawbacks these advanced post-LIBs must overcome before commercializing them is their short cycle life. We can see from Fig. 3c that, except for sodium-sulfur batteries, all other advanced batteries have a cycle life below 500 cycles. In addition to technical dilemmas concerning cathode electrochemistry, safety concerns are still related to morphology changes in cycling lithium metal as the anode. If traditional anodes (graphite) are applied, Li-air batteries lose much of their theoretical specific energy [34].

2.4. Hydrogen fuel cells

Instead of storing electricity in LIBs, FCEVs use hydrogen as fuel and convert it into electricity through a fuel cell stack [8]. Many fuel cell systems exist today, such as proton exchange membrane, solid oxide, molten carbon, phosphoric acid, and alkaline fuel cells [35]. Among them, hydrogen proton exchange membrane fuel cells are the dominant technique for transportation due to their fast start-up, high power density, high efficiency, and low operating temperature [35]. Using hydrogen as fuel has many merits—zero pollution after combustion, quick refueling, and high specific energy. The specific energy of hydrogen (120–142 MJ/kg) is two times higher than that of other more conventional fuels such as gasoline (44–46 MJ/kg) and diesel (42–46 MJ/kg), as shown in Fig. 3d. Hydrogen produced from various sources is classified by color. As there is no official consensus on the color classification of hydrogen, we referred to the guidance on the hydrogen color spectrum by the North American Council for Freight Efficiency [36], as shown in Figure 4. Green hydrogen (Figure 4a) is the most desirable hydrogen source, produced via water electrolysis using electricity from clean sources (e.g., solar, hydro, and wind power). Blue hydrogen (Figure 4b) and turquoise hydrogen (Figure 4c) can also be valued as

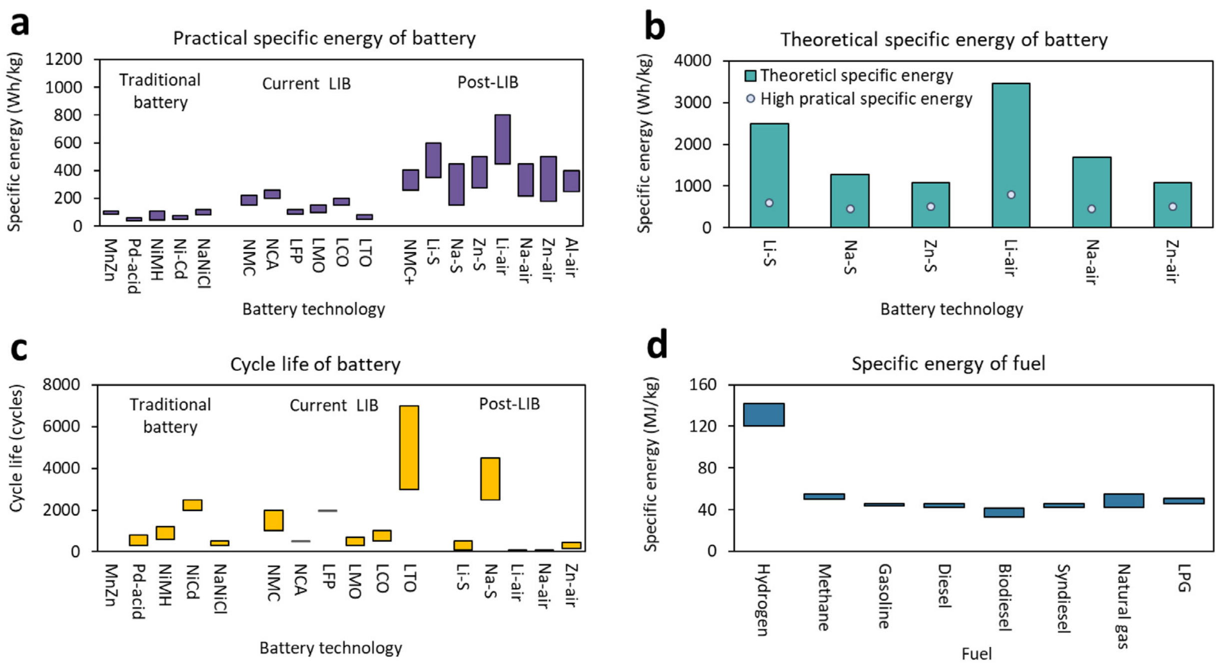

Fig. 3. (a) Practical specific energy of battery technologies, (b) theoretical specific energy of battery technologies, (c) cycle life of each battery, and (d) specific energy of fuel. MnZn: alkaline manganese-zinc, Pd-acid: lead-acid, NiMH: nickel-metal hydride, NiCd: nickel-cadmium, NMC: lithium nickel-manganese-cobalt oxide, NCA: lithium nickel-cobalt-aluminum oxide, LFP: lithium iron phosphate, LMO: lithium manganese oxide, LCO: lithium cobalt-oxide, LTO: lithium titanium-oxide, NMC+: advanced metal-anode/anode-free NMC, Li-S: lithium-sulfur, Na-S: sodium-sulfur, Zn-S: zinc-sulfur, Li-air: lithium-air, Na-air: sodium-air, Zn-air: zinc-air, Al-air: aluminum-air, syndiesel: synthetic diesel, LPG: liquefied petroleum gas. Supporting data for this figure are given in Tables A3 and A4 in the Appendix.

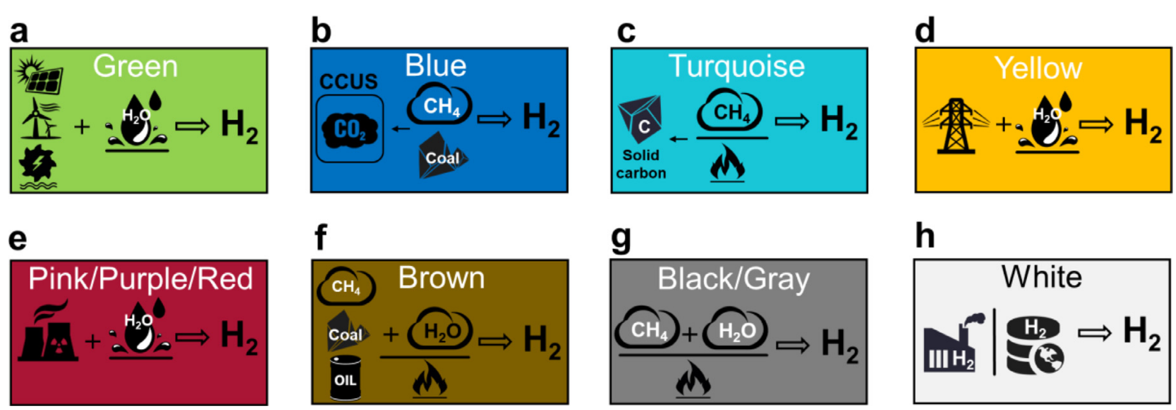

Fig. 4. Color spectrum for hydrogen production. (a) Green hydrogen, (b) blue hydrogen, (c) turquoise hydrogen, (d) yellow hydrogen, (e) pink/purple/red hydrogen, (f) brown hydrogen, (g) black/gray hydrogen, and (h) white hydrogen. CCUS: carbon capture, utilization, and storage.

low-carbon hydrogen. Blue hydrogen is produced primarily from natural gas through steam-methane reforming (SMR) with the application of carbon capture, utilization, and storage (CCUS). Turquoise hydrogen is a new entry in the hydrogen color spectrum, using methane pyrolysis to produce hydrogen and solid carbon. Yellow hydrogen (Figure 4d) is produced from water electrolysis using grid electricity. Pink/purple/red hydrogen (Figure 4e) is produced by electrolysis using nuclear power. Brown hydrogen (Figure 4f) is extracted from fossil fuels, such as oil and natural gas but normally coal, using gasification. Black/gray hydrogen is a specific brown hydrogen (Figure 4g) extracted via SMR without applying CCUS, which is the most used approach for hydrogen production. In 2020, approximately 76% of the hydrogen produced globally was from SMR [37]. White hydrogen (Figure 4h) is a by-product generated from the production of many industrial processes. White hydrogen is also used to describe the naturally-occurring geological hydrogen found in underground deposits created via fracking [38].

2.5. Critical metals used for automobiles

EVs consume six times more critical minerals than ICEVs [11]. The IEA identified nine critical metals for clean energy transition, including copper, cobalt, nickel, lithium, REEs, chromium, zinc, PGMs, and aluminum, and compared their criticality to different sectors [11], as shown in Fig. 5. Regarding the automotive sector, BEVs, PHEVs, and HEVs are more sensitive to copper, cobalt, nickel, lithium, REEs, PGMs, and aluminum. Cobalt, nickel, and lithium are the primary raw materials for the current cathode of LIBs. Aluminum and copper are manufactured as a foil to be used as current collectors at the cathode and anode,

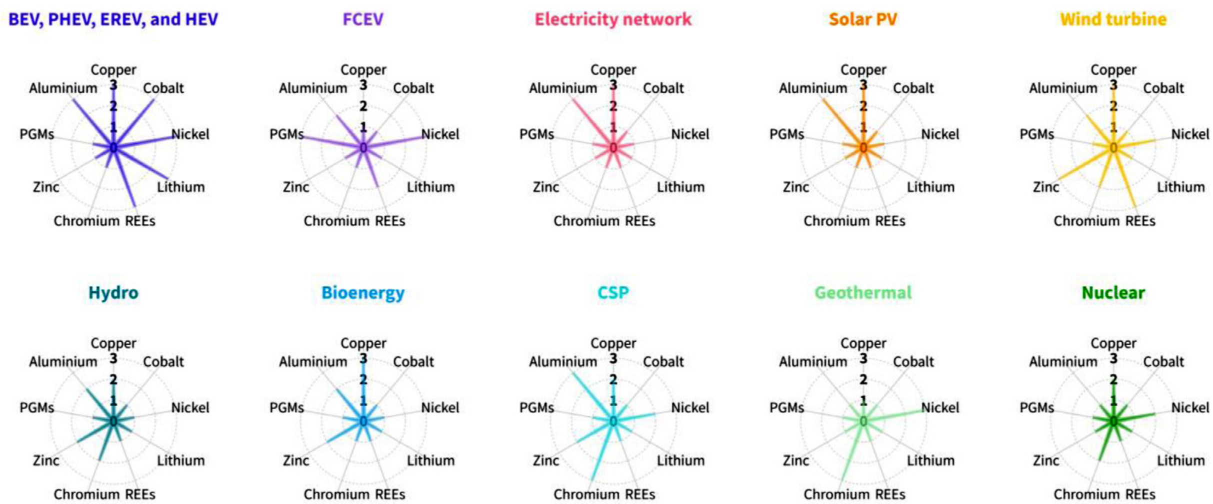

Fig. 5. Criticality of metals for the clean energy transition. BEV: battery electric vehicle, PHEV: plug-in hybrid electric vehicle, HEV: hybrid electric vehicle, FCEV: fuel cell electric vehicle, REEs: rare earth elements, PMGs: Platinum group metals, PV: photovoltaic, CSP: concentrated solar-thermal power. Scale: "1″ means low criticality, "2″ denote moderate criticality, and "3″ denote high criticality. Data is derived from IEA [11].

respectively, in an LIB to ensure the stability of the current collector. It is worth noting that aluminum and copper are the main raw materials for the entire automotive industry. REEs, especially the most critical ones, neodymium and dysprosium [39], are used to manufacture permanent magnets for electric motors in EVs. In contrast, FCEVs depend more on PGMs (e.g., platinum, rhodium, and palladium [40]) and nickel, which are used to catalyze the sluggish oxygen reduction reaction at the cathode in a proton exchange membrane fuel cell stack.

3. Methods

Relevant articles were retrieved from the Web of Science Core Collection, including (i) Science Citation Index Expanded (SCIE), (ii) Social Sciences Citation Index (SSCI), (iii) Arts & Humanities Citation Index (A&HCI), (iv) Emerging Sources Citation Index (ESCI). The Boolean function was used (including quotation marks and capitalization) to gather articles from Core Collection as follows:

TS = (((“material requirement”) OR (“material demand”) OR ("material flow analysis") OR (MFA) OR (“substance flow analysis”) OR (SFA) OR ("material stock") OR ("material flow")) AND (("electric vehicle") OR (EV) OR (“transport electrification”))).

Since the launch of the Electric Vehicle Initiative, an international government policy forum, in 2010, policies have been enacted to accelerate the global adoption of electric vehicles [41]. Therefore, the search covers the period from January 1st 2010 to the time the literature was gathered, October 1st 2022, in the Web of Science Core Collection and yielded 79 records. These records are further filtered based on the following criteria: (i) the paper should focus on the material requirement of the automotive sector; (ii) the paper should be full-length research articles as opposed to review- or comment-type papers. This resulted in 30 articles that fit the scope of our review and additional 48 articles selected via snowballing from the obtained 30 articles, summing up to 78 research articles (See Table A5 in the Appendix). The 78 articles are screened for further analysis from the following eight aspects:

- Timeframe of the projection (e.g., retrospective, or prospective)
- Geographic focus (e.g., regional, national, and global levels)
- Focus of the transportation sector (e.g., private, and commercial sectors)
- Type of EV technologies (e.g., BEVs, PHEVs, HEVs, and FCEVs)
- Type of battery technologies (e.g., NMC, and LFP batteries)
- Type of materials (e.g., lithium, nickel, and graphite)
- Type of methodological contributions (i.e., stock-driven, and flow-driven)
- Type of policies (e.g., technological advancement, primary production expansion, and upscaling recycling)

We also further gather and analyze the projections of future global requirements for those metals that received the most attention from the selected studies: lithium, nickel, cobalt, and PGMs. We compare the annual and cumulative demand for these four types of metals in different studies with their current production capacities and reserves. Manganese is also a critical element for NMC batteries [7]. Since manganese reserves have been proved to be sufficient to meet the needs of the LIBs industry [42], a summary of projections for manganese demand is omitted. Moreover, REEs consists of 17 metallic elements, and most studies did not investigate a full range of REEs. Similarly, copper and aluminum are used for LIBs and other components in the automotive industry. Therefore, REEs, copper, and aluminum are also not analyzed to reduce the scope discrepancy in those projections. Then we categorize and summarize the policy implications from selected papers. Finally, we discuss the main findings from the four aspects: environmental and social implications of deploying electric vehicles, whether or not to electrify heavy-duty vehicles, opportunities and challenges in recycling, and future research direction.

4. Characteristics of the selected studies

4.1. Temporal and geographical scope

Fig. 6 shows the distribution of selected studies by publication years and focus regions. The number of publications is generally on the rise and has grown rapidly since 2016, as shown in Fig. 6. The temporal scope of these studies ranges from 1975 to 2100. 86% of the studies use a prospective approach to forecast future material demand, as shown in Fig. 7a. We further categorize those prospective studies based on their horizons into (i) short-term prospective, investigating the material requirement in the near future from 2020 to 2030; (ii) medium-term prospective, focusing on the period of 2020–2050, (iii) long-term prospective, indicating a long-run projection for 2020–2100. Approximately 66% of the prospective studies aimed for a medium-term projection, and 82% of the medium-term projections chose 2050 as the final year for their projections, as 2050 is the critical time point when anthro-

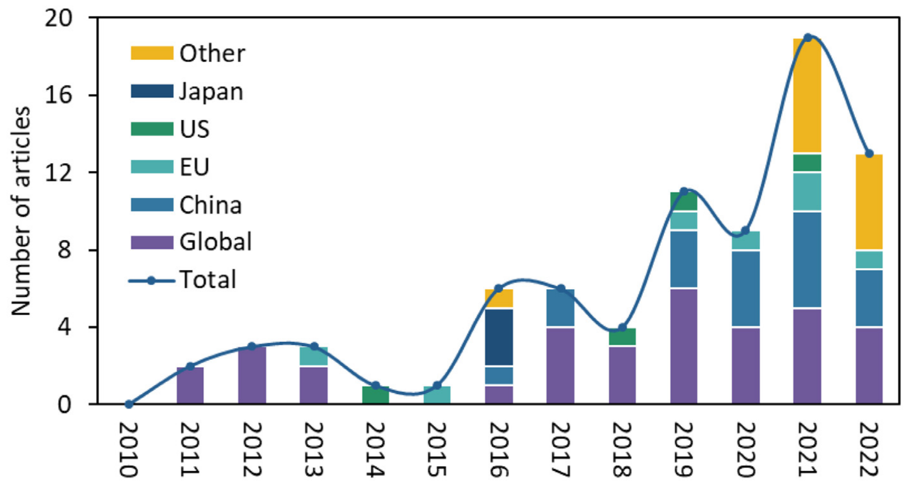

Fig. 6. Chronology and geographical scope of studies related to the material requirement for transportation electrification. “Global” represents a planetary boundary, EU denotes the European Union, US means the United States, and “Other” refers to countries and regions other than China, the US, and Japan.

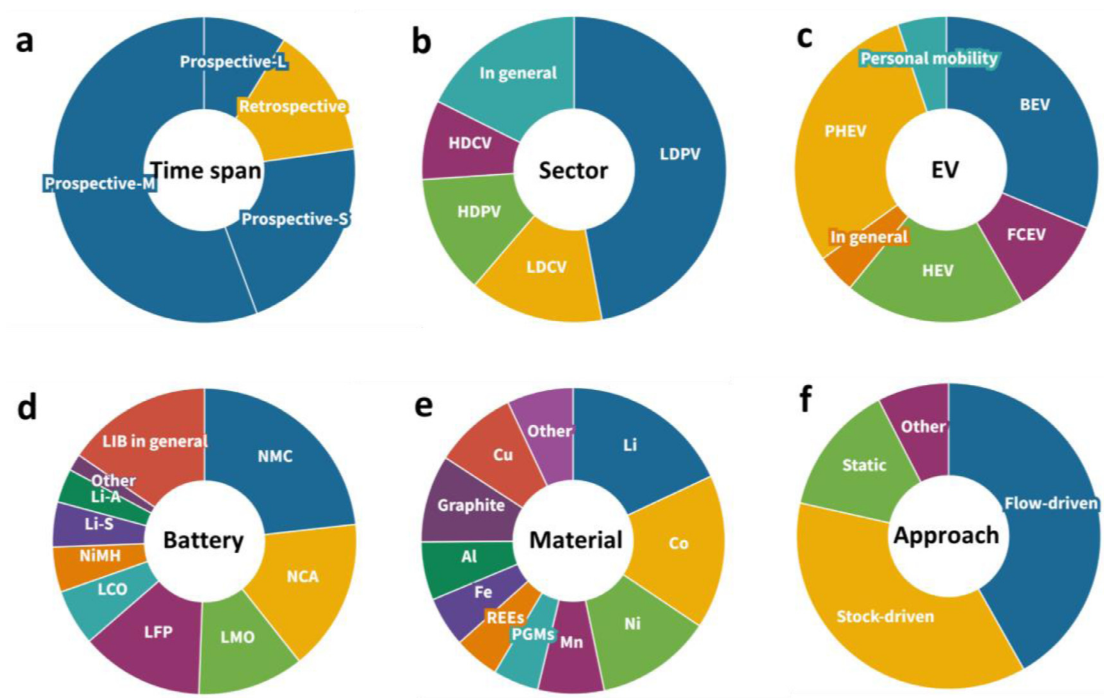

Fig. 7. (a) Time span, (b) sectors, (c) electric vehicle technologies, (d) battery technologies, (e) materials, and (f) used approaches of analyzed studies. The sector's share depends upon the number of articles that study it. Prospective-L: long-term prospective, Prospective-M: medium-term prospective, Prospective-S: short-term prospective, LDPV: light-duty passenger vehicle, LDCV: light-duty commercial vehicle, HDPV: heavy-duty passenger vehicle, HDCV: heavy-duty commercial vehicle, BEV: battery electric vehicle, PHEV: plug-in hybrid electric vehicle, HEV: hybrid electric vehicle, FCEV: fuel cell electric vehicle, REEs: rare earth elements, PMGs: Platinum group metals, NMC: lithium nickel-manganese-cobalt oxide, NCA: lithium nickel-cobalt-aluminum oxide, LFP: lithium iron phosphate, LCO: lithium cobalt oxide, LMO: lithium manganese oxide, NiMH: nickel metal hydride, Li-air: lithium-air, Li-S: lithium-sulfur. Personal mobility includes electric scooters, electric bicycles, and electric tricycles.

pogenic GHG emissions are expected to reach “net zero” [43]. Almost all long-term projections set 2100 as the final year, as 2100 is the year to achieve the 2°C global warming limit goal [44]. In terms of geographical boundaries, 44% of the total studies were conducted from a worldwide/global perspective, followed by China (23%), the European Union (9%), and the United States (5%), which are the currently three largest EV markets in the world [12]. Some global studies also reveal regional specifics, such as [16,45–53]. A few studies focus on region- or city-level assessments, such as Catalonia, Spain [54], Fujian, China [55], California, the U.S. [56], and Vienna, Austria [57].

4.2. Transportation sectors and electric vehicles

The focused transport sectors are divided into four categories, light-duty passenger vehicles (LDPVs), light-duty commercial vehicles (LDCVs), heavy-duty passenger vehicles (HDPVs), and heavy-duty commercial vehicles (HDCVs), as demonstrated in Fig. 7b. Metal requirement for electrifying LDPVs is the most studied area, summing up to 56 papers, as passenger vehicles are the most important sector for electrification and will make up more than 80% of the total in-use road fleet worldwide by 2100 [40]. The HDCV sector is the least researched area, with only ten papers examining it. Twenty-one papers did not specify the exact areas they studied but addressed the road transportation sector in general.

Regarding powertrains (see Fig. 7c), BEVs and PHEVs are the most researched, accounting for 60 and 57 papers, respectively. They are the currently most widespread EV technologies for transportation electrification [41]. HEVs and FCEVs gained less attention, with 37 and 20 papers focusing on them, respectively. Ten studies also concern emerging personal mobile solutions such as electric bicycles/two-wheelers [16,57–63], electric tricycles/three-wheelers [59,62], and electric scooters [57]. The other eight papers did not specify the types of EVs they studied.

4.3. Batteries

There are ten types of batteries mentioned in the selected studies: (i) NMC batteries, (ii) NCA batteries, (iii) LFP batteries, (iv) lithium cobalt oxide (LCO) batteries, (v) LMO batteries, (vi) NiMH batteries, (vii) Li-air batteries, (viii) lithium-sulfur (Li-S) batteries, (ix) Pd-acid batteries, and (x) alkaline manganese-zinc batteries, as shown in Fig. 7d. NMC, NCA, and LFP batteries are the three most studied battery technologies, accounting for 50.0%, 34.6%, and 28.2% of the total analyzed papers, respectively (see Fig. 7d). In contrast, emerging LIB technologies such as Li-air and Li-S batteries have received less attention. It is noted that 33.3% of papers did not specify the type of LIBs they analyzed.

4.4. Materials

The investigated materials include lithium, cobalt, nickel, manganese, PGMs, REEs, iron, aluminum, graphite, copper, and other materials (e.g., lead, tantalum, boron, zinc, magnesium, chromium, and titanium), as depicted in Fig. 7e. Three metals for battery cathode have received the most attention, and 52.6%, 47.4%, and 35.9% of the papers investigated lithium, cobalt, and nickel, respectively. Other battery materials received less attention: 26.9% for graphite, 25.6% for copper, 20.5% for manganese, and 17.9% for aluminum, respectively. Only 14.1–15.4% of the papers explored PGMs, REEs, and iron. Regarding materials to be tracked, most studies have focused on one or a few specific materials, while some assess batteries needed by weight or number of packs [56,64–66]. A few studies also investigated gross direct materials used for vehicles [67,68]. Kosai et al. [69] and Watari et al. [70] used the “total material requirement” method to assess the direct and indirect materials used for vehicles.

4.5. Modeling approaches

Four types of modeling approaches are used to conduct an MFA: (i) dynamic approaches, including stock-driven and flow-driven models, (ii) static approach, and (iii) other approaches, as illustrated in Fig. 7f. The stock-driven and flow-driven approaches are used most to project future material requirements, accounting for 33 and 29 papers, respectively. They both rely on a key parameter—the life span of vehicles or batteries—to convert the annual in-use stocks and sales to the final material demand. Only 12 papers used a static analysis and reported metal demand for one specific past year, including 2007 [71], 2009 [72], 2011 [46], 2014 [16], 2015 [58], 2016 [63,73], 2017 [74,75]; or a time span of past years: 2001–2013 [76], 2006–2015 [60], 2000–2018 [62]. Five papers applied other approaches to forecast the future material requirement for transportation electrification but aimed to directly model the material demand rather than assuming a lifetime, such as linear regression [77–79], and increase rate [79,80].

5. Summary of critical metals projection

5.1. Annual material requirement

We summarize the global annual requirement for lithium, nickel, cobalt, and PGMs, as shown in Figs. 8–11. The projected demand for each metal in each case should not be directly comparable due to different goals and scopes. Still, the analysis could shed light on the future critical metal need for transportation electrification. For short- and medium-term forecasts of lithium demand (Fig. 8), almost all studies point to an increase from 8 to 242 Kt in 2020 to a maximum of 2079 Kt in 2050, far exceeding the current lithium production of 100 Kt in 2021 [42]. Due to the rapid deployment of EVs, approximately 74% of the lithium produced in 2021 was used in the LIB industry [81]. Habib et al. [82] found that the in-use EV stocks will continue to grow in an “S” shape and reach saturation in 2050. Consequently, the lithium demand will peak in 2035 and gradually decrease to near zero. Regarding long-term forecasts, Kushnir and Sandén [83] found the lithium requirement peaks in 2045 with a range of 941–1849 Kt and then stabilizes at approximately 400–1000 Kt in 2070. In the simulation study by Harvey [84], the lithium demand will stabilize at approximately 700–1100 Kt much later, around 2080. In contrast, Hao et al. [85] predicted that the lithium need will monotonously increase to 1719– 2031 Kt by 2100.

Fig. 9 shows the worldwide annual nickel requirement projections, which generally present an ascending trend in the short and medium terms in those studies [52,53,86–88]. In the simulation by Habib et al. [82], the annual nickel requirement is supposed to peak in 2030 in the range of 880–4451 Kt and then decline to nearly zero due to the saturation of EVs as well. In one of the scenarios considered by Dunn et al. [52], the nickel requirement will gradually phase out by 2040 as NMC and NCA batteries were assumed to be completely replaced by LFP batteries. The 2021 nickel production capacity was 2700 Kt [42], 11% of which was used in the LIB industry [89]. By 2050, the current production capacity would probably not be able to meet any of either scenario based on the simulation.

Fig. 10 depicts the future cobalt requirement for EV batteries worldwide. 170 Kt of cobalt was produced in 2021 [42], of which approximately 40% was used to make LIBs, and that share will expand to 53% due to the extensive deployment of EVs [90]. Likewise, the short- and medium-term annual cobalt requirements are supposed to grow by 2050 in most cases. Yet, the annual requirement of cobalt presents an “inverse-U” shape in some cases because of the saturation of the EV market [82], material proportion design upgrading of NMC batteries [88], and the development of zero-cobalt LFP technologies [51,52]. Regarding the long-term projection of Harvey et al. [84], the cobalt demand will increase and remain stable at 1300–2200 Kt around 2080, similar to the trend for lithium and nickel.

The projected trends for PGMs in the selected studies are relatively consistent (Fig. 11), with almost monotonic growth over the time span investigated. The production capacity of PGMs in 2021 was estimated to be only 380 tons, including 200 tons of palladium and 180 tons of platinum [42], of which about 148 tons will be applied to the automotive industry [91]. The future annual demand for PGMs will be well above the production capacity in 2021, ranging from 109 to 1033 tons by 2030 and 302–2521 tons by 2050. Those long-term projections will lead to a larger range of uncertainty, 299–8377 tons by 2100.

Major uncertainties exist in those projections. The main factors of uncertainties are the penetration rate of EVs, the saturation of the EV market, PGM loading, material proportion design of LIBs, the focused sectors for adopting EVs, and the technological development of batteries. Scenario analysis is the primary method for modeling and examining those uncertainties in critical metal demand of transportation electrification in those prospective studies. For example, raising the market share of FCEVs from 0% to 100% by 2100 would increase the annual PGM requirement from 1587 tons to 8377 tons [45]. Reducing the PGM loading of fuel cell systems is supposed to halve the total demand of the heavy- and light-duty sectors in 2100 [40]. Regarding the sector to electrify, the heavy-duty sector accounted for 19% of the PGM use [40] and 62% [85] of the lithium use in 2100. The zero-cobalt battery technics can reduce the use of cobalt to zero in 2050 [51]. Although these uncertainties, there are two trends of future annual demand forecasts—

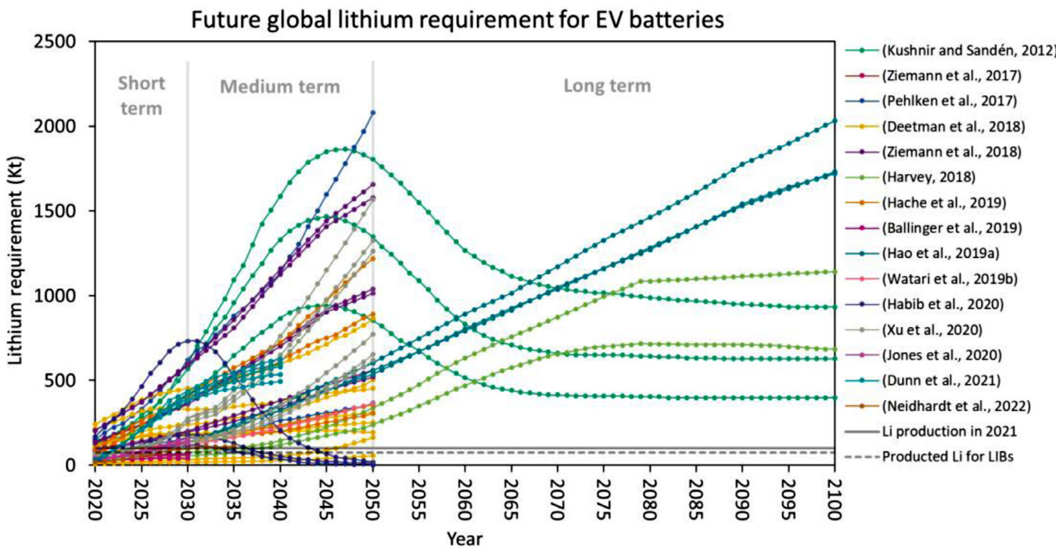

Fig. 8. Projections of global lithium requirement for electric vehicle (EV) batteries. Note: Data for lithium production in 2021 is derived from the United States Geological Survey (USGS) [42].

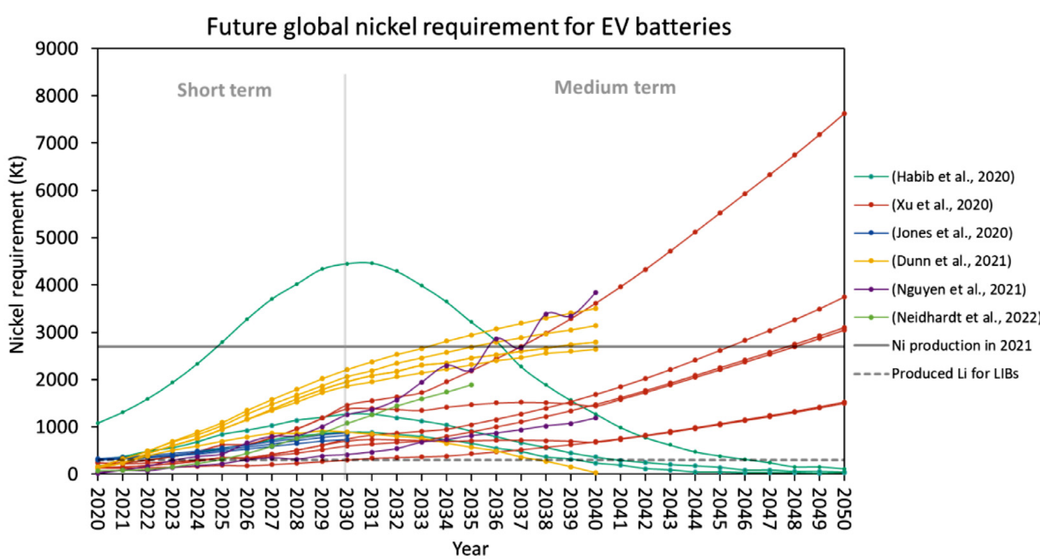

Fig. 9. Projections of global cobalt requirement for electric vehicle (EV) batteries. Note: Data for nickel production in 2021 is derived from USGS [42].

monotonic increase is the most general trend by 2050, and some minor scenarios also present an "inverse-U" trajectory, primarily resulting from market saturation and technological disruption.

5.2. Cumulative material requirement

Projections of the cumulative requirement for lithium, nickel, cobalt, and PGMs are calculated as shown in Fig. 12. Those estimates are subject to significant uncertainties. Cumulative demand for lithium ranges from 154 to 5115 Kt by 2030 and is capped at 33,051 Kt by 2050 and will continue to increase to 33,641–88,614 Kt by 2100, remarkably surpassing the current lithium reserves of 22,000 Kt [42]. The cumulative requirement for nickel is 2119–30,870 Kt by 2030 and will increase to 5438–88,857 Kt by 2050. The nickel reserves were estimated at least 95,000 Kt by 2021 [42], slightly above its maximum cumulative demand for nickel by 2050 but probably insufficient to meet the cumulative demand by 2100. The cumulative requirement for cobalt is more uncertain, ranging from 27 to 4689 Kt by 2030 to 117–18,069 Kt by 2050. By 2100, the cumulative cobalt requirement will soar to 65,426–97,461Kt, yet global cobalt reserves are only 7600 Kt. The cumulative requirement for PGMs is much smaller than for lithium, nickel, and cobalt, at approximately 1–9 Kt by 2030, 3–29 Kt by 2050, and 14–260 Kt by 2100, respectively. The PGM reserves in 2021 were around 70 Kt. Similar to nickel, the reserves of PGMs should meet their cumulative demand by 2050 but may be insufficient by 2100. Therefore, reserves of those metals may meet the short- and medium-term requirements related to global transportation electrification but are unlikely to meet long-term needs. It is also noteworthy that a certain portion of the reserves of each metal is also for other applications, while the share of the reserves for automotive is supposed to increase. Additionally, reserves of each critical metal also change over time due to new geological discoveries and technological advancements.

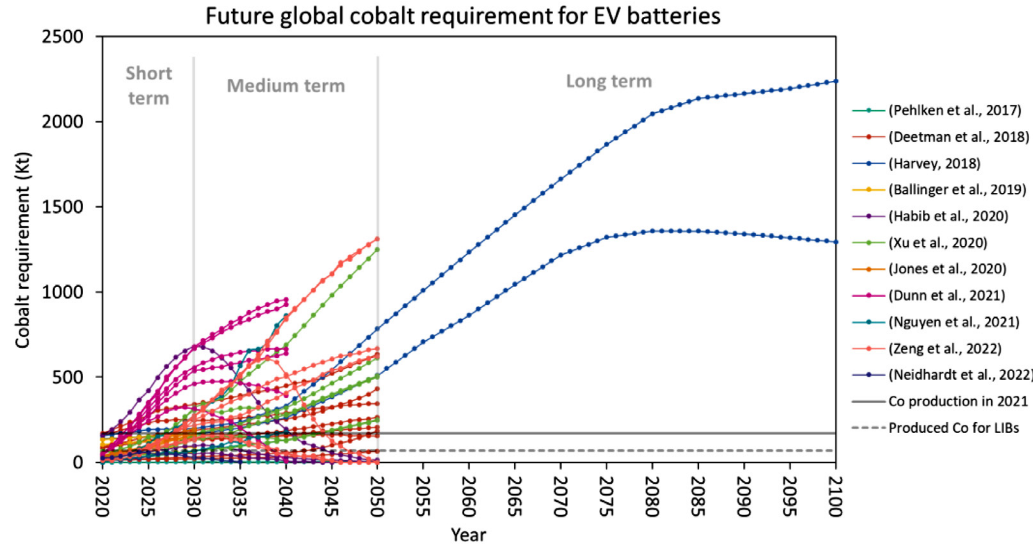

Fig. 10. Projections of global nickel requirement for electric vehicle (EV) batteries. Note: Data for cobalt production in 2021 is derived from USGS [42].

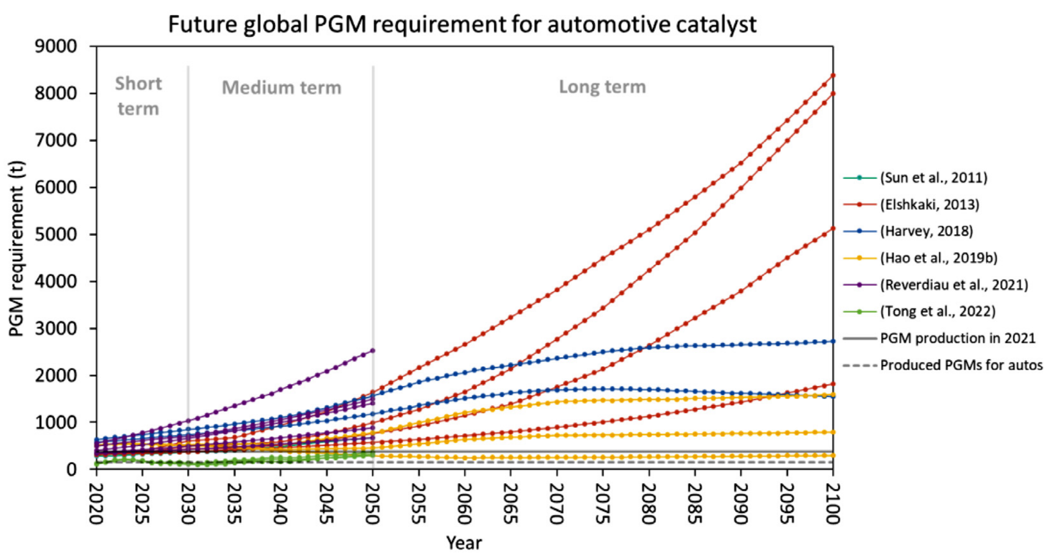

Fig. 11. Projections of global platinum group metals (PGMs) requirement for automotive catalyst. Note: Data for PGM production in 2021 is derived from USGS [42], and only the production of palladium and platinum is considered due to data availability. Around 36–42% of the PGMs are used in the automotive sector [91].

6. Summary of policy implications

Based on the analysis of the expected critical metal demand for transportation electrification, relevant policies have been proposed in the selected studies to ensure future metal supply, as shown in Table A5 in the Appendix. Those policies can be generally classified into four types: (i) technology-oriented, (ii) supply-oriented, (iii) demand-oriented, and (iv) regulatory-oriented. Technology-oriented policies encourage technological advances, mainly through recycling, reuse, and battery design. Supply-oriented policies intervene in the supply of materials by expanding ore mining and production capacity, upscaling the use of recycling and associated secondary materials, etc. Demand-oriented policies focus on reducing the demand for critical metals, such as promoting public transportation, adopting alternative automobiles, e.g., FCEVs, and improving material efficiency and lightweight design. Regulation-oriented policies emphasize the establishment of laws, norms, and industrial standards to regulate the production, recycling, and disposal of LIBs and fuel cell systems.

We further categorized those policy implications and summarized them in Table 1. There are nine types of policies: those related to (i) mining, (ii) research & development, (iii) manufacture, (iv) sale, (v) use, (vi) end-of-life (EoL) treatment, (vii) international trade, (viii) organization & cooperation, and (ix) standardization & regulation. The main stakeholders in the value chain of EVs include (i) industrial entities such as suppliers and manufacturers, sellers, and recyclers, (ii) governments, (iii) non-governmental organizations such as universities, institutes, and industrial associations, etc., and (iv) customers. Most policies focused on EoL treatment, especially promoting recycling and reuse. It is noted that customers can also play a role in reducing critical metal use by extending the service life of vehicles and shifting to a shared- and public-based mobility mode.

Table 1
Categorization of the proposed policies for securing critical metal supply.

Category	Policy	Reference
1 Mining	1.1 Maintain a portfolio of known resources	[63,83]
	1.2 Penalize the use of raw ore by tighter environmental and resource restrictions	[76]
	1.3 Expand domestic mining	[16,92–95]
	1.4 Explore mining	[51,58,61,96,97]
	1.5 Stockpile raw materials	[40,58]
	1.6 Improve mining efficiency	[51,60]
	1.7 Interconnection with different materials in all the life cycle stages	[63]
2 Research & development	2.1 Improve battery design for repairing, disassembly, recycling, and reuse	[51,54,55,70,74,98–100]
	2.2 Promote battery substitution design	[51,82,101]
	2.3 Promote battery technological innovation	[62]
	2.4 Extend battery lifetime	[87,102]
3 Manufacture	3.1 Mandate properties instead of the secondary composition of a product	[98]
	3.2 Use secondary material	[98]
	3.3 Promote efficient production to reduce raw material use	[49,51,52,71,92,102,103]
	3.4 Material substitution	[49–51,53,55,60,61,74,96,102]
	3.5 Improve loss in the manufacturing phases through recovering process scrap	[55,104]
	3.6 Increasing other coproduced metals	[93]
	3.7 Extended producer responsibility system	[50,51,54]
	3.8 Carefully consider the electrification in the heavy-duty segment	[85]
4 Sale	4.1 Encourage technological innovation for EVs through subsidy or tax exemption in purchasing	[40]
	4.2 New business model	[74,105]
	4.3 Balance the development and use of different types of batteries	[92,103]
	4.4 Marketing alternative EVs (e.g., FCEVs) to save certain materials	[95,106]
	4.5 Bring other vehicle technologies to competitive readiness	[83]
5 Use	5.1 Extend service life	[55,102]
	5.2 Shift to a shared and public mobility mode	[51,104,105,107]
6 End-of-life	6.1 Promote accountability and traceability of EoL flows	[74,101,105]
	6.2 Promote collecting	[51,57,63,74,76,80,101,105,107,108]
	6.3 Promote sorting	[64,80,98,102]
	6.4 Promote recycling	[16,39,40,49–64,66,68–70,73,74,76,77,80,83,84,86–88,92–96,98–114]
	6.4.1 Consider environmental implications and absolute quantities	[70]
	6.4.2 Do not rush into EoL recycling as it has limited impacts on short/medium-term	[104]
	6.4.3 Avoid a surplus of secondary supply and consider open-loop recycling	[68,98,103]
	6.4.4 Industrialize the recycling industry	[52]
	6.4.5 Set minimum recycling content targets	[54,111]
	6.4.6 Improve recovery efficiency and innovative technologies	[39,40,50,51,54,64,87,88,100,101]
	6.4.7 Incentivize recycling enterprises	[76,97]
	6.4.8 Promote cost-effective recycling	[98]
	6.4.9 Increase recycling rate	[49,60,84,102]
	6.5 Promote reuse	[54,56,62,65,68,93,100,102,103,106–108,114]
	6.5.1 New business model for second use	[65]
	6.5.2 Develop second-use markets	[110]
	6.5.3 Minimum second-use targets	[54,111]
	6.5.4 Prioritize reuse to recycling	[100,106]
	6.6 Scrap recovery and sorting in nonautomotive sectors	[98]
	6.7 Establish a comprehensive EoL LIB waste management system	[73,74,101,106]
	6.8 Balance recycling and reuse	[88]
7 International trade	7.1 Export scrap for sorting and recycling	[98]
	7.2 Expand raw material imports	[16,58,80,92,95,115]
	7.3 Enhance trading network and joint resource development	[40,63]
8 Organization & cooperation	8.1 Cooperation and joint efforts between governments, battery researchers, automotive and battery manufacturers, consumers, and recycling companies to boost recycling.	[40,99,102]
	8.2 Plans on the number of collection stations	[66]
	8.3 Regional-specific EoL management strategies such as various densities of stock, secondary market, and existing infrastructure	[56]
	8.4 International-level technology sharing and transfer from the technology-leading countries and enterprises to their counterparts in the developing world	[40]

(*continued on next page*)

Table 1 (*continued*)

Category	Policy	Reference
	8.5 International cooperation on waste management	[40]
	8.6 Public sectors should make concerted efforts to facilitate partnerships for recycling	[56]
9 Standardization & regulation	9.1 Standardize battery design of battery chemistries, types and sizes, and labeling of cells for better sorting, reusing, and recycling	[40,51,99,105,113]
	9.2 Standardize the recycling process	[66,102]
	9.3 Unify battery types and sizes of the retired batteries for reuse and recycling across regions	[113]
	9.4 Enact laws or regulations on recycling	[51,61,97]
	9.5 Enact regulation on limiting disposal	[50]
	9.6 Safety certificate for second use	[66]
	9.7 Bans of some specific LIB chemistry or substance	[111]

7. Discussion

7.1. Environmental and social considerations of deploying electric vehicles

The trade-off in adopting EVs is clear—investing in more critical metals to generate clean electricity than burning fossil fuels. Significantly more critical metals are used to manufacture EVs than conventional ICEVs [11], not to mention the critical metals (see Fig. 5) used to generate clean electricity to power EVs. Therefore, electrification will transform the transportation sector from a fossil fuel-intensive industry to a material-intensive one, exacerbating the existential threat to critical metal supply. Moreover, using electricity to propel vehicles shifts the GHG emissions from transportation to power generation, and empowering EVs with fossil fuel-based electricity does not necessarily reduce GHG emissions. Knobloch et al. [116] found in most countries surveyed, the adoption of PHEVs is supposed to reduce life-cycle GHG emissions compared to traditional ICEVs, even before the power sector is fully decarbonized. Yet, some exceptions exist (e.g., India, China, and Russia). Specifically, adopting four-wheeler BEVs in India, where coal-fired power plants generate a large share of electricity, may lead to increasing GHG emissions in 18 of the 32 investigated states and Union territories, even if 2030 targets for India under the 2021 United Nations Climate Change Conference (COP26) are met [117]. The power grid of India has to decrease its GHG emissions by 38–52% for the incoming electrification waves [117]. Liu et al. [118] also found that deploying BEVs in some provinces in China can lead to significant rebound effects in GHG emissions. Urgent coordination of power and transport sectors on decarbonization becomes more important to achieve a net-zero carbon

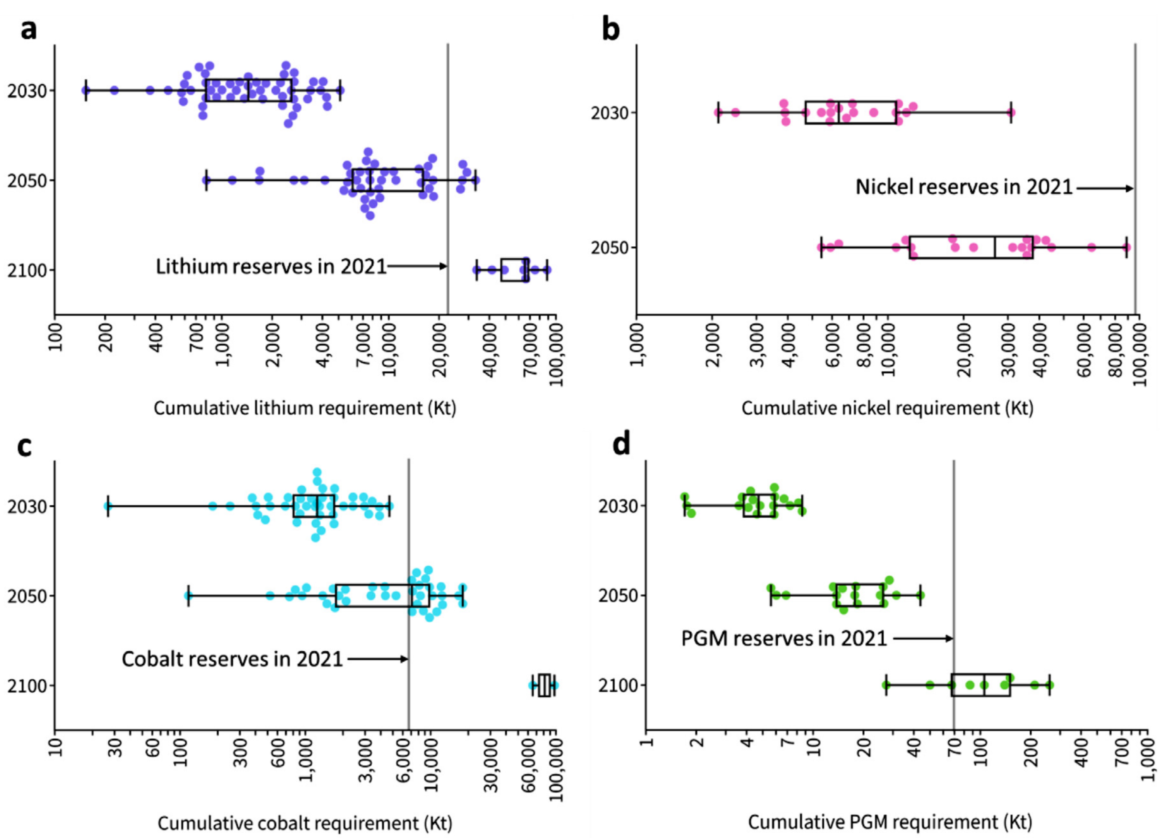

Fig. 12. Projection of cumulative requirements for (a) lithium, (b) nickel, (c) cobalt, and (d) platinum group metals (PGMs). Note: Data for reserves of lithium, nickel, cobalt, and PGMs are derived from USGS [42].

target at the whole system level. To ensure a sustainable transformation of the transportation sector, we need to improve the material efficiency in the use of critical metals on the one hand and keep the decarbonization of the power sector in parallel with the diffusion of EVs on the other hand.

In addition, the production of critical metals is highly concentrated in small countries such as the Democratic Republic of the Congo, Chile, and South Africa [42]. In 2021, around 71% of the cobalt was produced in the Democratic Republic of the Congo [42], with 15–20% being extracted by artisanal miners [119]. This has caused serious social, ecological, and health problems for local people in Democratic Republic of the Congo, such as child labor [120], severe environmental pollution and the consequent exposure-related oxidative DNA damage [119]. Besides the economic viability, making the critical metal supply chain environmentally and socially sustainable is a substantial challenge we must face in the clean energy transition.

7.2. Electrification of heavy-duty vehicles

Fig. 7b shows that light-duty vehicles are the heart of future transportation electrification, representing more than 80% of the total in-use road fleet worldwide [40]. Heavy-duty vehicles make up only approximately 5% [40], while their battery capacities (517–1074 kWh per BEV and 93–202 kWh per PHEV [85]) and fuel cell powers (85–340 kW per FCEV) are much higher than light-duty vehicles, resulting in higher material intensity for those critical metals. In addition, heavy-duty vehicles must replace their battery packs once during their lifetime, increasing the demand for LIB-related raw materials [24]. Hao et al. [85] found that lithium used for heavy-duty BEVs and PHEVs could make up 62% of the total lithium requirement in 2100, of which about 49% is due to battery replacement.

As a result, the existing resource of those critical metals may not sustain extensive electrification in both light and heavy sectors. Thus, governments and automotive industries should approach the electrification of heavy-duty vehicles with caution. Regarding countermeasures, improving the durability of batteries to avoid battery replacement for heavy-duty BEVs and PHEVs could largely reduce the material requirement for LIBs. Moreover, deploying alternative EVs (e.g., FCEVs and biofuel-based vehicles) can also save a certain amount of materials. Hao et al. [40] found that light-duty FCEVs will require 81% of the PGMs in 2100, while PGMs for heavy-duty FCEVs will only account for the remaining 19%. Harvey [84] came to similar conclusions, with heavy-duty vehicles accounting for 30–32% of the total demand for PGMs in 2100. Despite the much higher power of heavy-duty vehicles, light-duty vehicles still represent the greatest demand for PGMs. Yet, increasing the use of PGMs to reduce the demand for lithium, cobalt, and other metals could still be a potential trade-off. Biofuel-based vehicles are alternative solutions to decouple the mitigation of GHG emissions in transportation from the dependence on critical metals [121].

7.3. Opportunities and challenges in recycling

Recycling is a key strategy to reduce virgin minerals and secure future material supplies. However, several challenges need to be addressed before recycling can be widely implemented. First, recovering critical metals from retired LIBs is theoretically viable, but more advanced and efficient technologies are in urgent need. The current technologies to recycle retired batteries include [122]: (i) pyrometallurgical process, (i) hydrometallurgical process, (iii) bio-metallurgical process, (iv) hybrid process that combines the first three processes, (v) direct cathode recycling, and (vi) second use. However, the facilities and processes for recycling LIBs are limited in terms of the quality, cost, environmental pollution, and energy usage of recycling metals [122]. Direct cathode recycling can potentially reduce emissions and be economically competitive but is currently less technologically ready [123]. LIBs that have reached the end of their first life (80% of initial energy storage capacity) can be reused as energy storage systems (ESSs) with a second life of 10 years before entering recycling plants [124]. Compared to the direct recycling of LIBs after EV use, LIBs reused after their first life as ESS can reduce energy use and GHG emissions by up to 6% and 17% [125]. Despite the gained benefits of reuse, all LIBs are still supposed to be recycled eventually. Methods such as enhancing traceability and collection and upscaling presorting of retired LIBs are essential to promote recycling. At present, however, it is difficult to find a profitable recycling process without substantial successful technological innovation and development. Thus, technological progress is the key to the circularity of the automotive industry in the future.

Second, it is also important to boost recycling at a proper pace. With the surge of EoL vehicles in the incoming decades, recycling will gradually become increasingly important to meet the needs of LIB cathode-related metals [86], PGMs [40], and REEs [96]. For instance, in the long run, Hao et al. [85] found that recycled lithium can substitute 84% of its demand in 2100. Thus, rushing into recycling in short/medium term not only has limited impacts but wastes resources [104]. On the other hand, governments and manufacturers should also be cautious about the oversupply of recycled materials due to material efficiency improvement in the future [68]. Although reusing retired vehicle LIBs for a second life may exacerbate the supply risk due to delaying recycling, properly balancing the reuse share could buffer the risk of oversupply without impeding secondary production. In addition, the reuse of LIBs could provide new opportunities for cheap battery energy storage systems with the associated cost reduction of a park-level integrated energy system [126]. The total stationary storage capacity of reused EV LIBs could exceed 200 GWh by 2030 [127]. Therefore, recycling facilities and infrastructure should be appropriately planned to match the local characteristics of EoL vehicle flows.

7.4. Future research directions

There are still some knowledge gaps worth further exploration. First, most cases simulated the critical metal demand based on the technologies of current batteries, namely NMC, NCA, and LFP. The impact of deploying emerging battery technologies, such as Li-air and sodium-sulfur (Na-S) batteries, on future critical material demand still needs comprehensive investigation. Furthermore, most cases focus on the global-level analysis, while studies on the detailed regional disparities under global prospects are rare. In addition, demand and secondary supply are the two aspects that received the most attention. However, studies on the primary supply, productive capacity, and relation between supply and demand should also be properly evaluated. Finally, various policies were proposed to ensure the future supply of critical metals. However, policies' priority, validity, and spatiotemporal specifications are supposed to be further quantitatively examined.

8. Conclusions

In this study, we conducted a comprehensive review of 78 research articles published between January 2010 and October 2022 regarding the metal requirements for transportation electrification. A comparative analysis was performed to examine the selected literature's geographical and temporal scopes, research approaches, forecast of future material demand, and proposed policy implications. The main conclusions can be summarized as follows.

- Focuses of studies on the critical metals for transportation electrification

Research interest in this domain has experienced a noticeable increase during 2019–2021. Most studies used the dynamic MFA model to investigate the future demand for metals, and they chose 2050 as the final year for their projections, as 2050 is the critical time point when most countries and regions are expected to reach carbon neutrality. Global-level metal demand has received the most attention, followed by China, the European Union, and the United States, currently the three largest EV markets. Regarding the focused transportation section, the light-duty passenger BEVs and PHEVs are the focal point for the assessment. Concerning battery technologies, NMC, NCA, and LFP batteries are the three most-emphasized types of batteries because they are and will be the most widespread traction battery technologies in the near term. Three battery-related metals, lithium, cobalt, and nickel, have gained the most attention.

- Projection of future critical metal demand

We compared the prospective global requirement of the four most studied metals for transportation electrification, namely lithium, nickel, cobalt, and PGMs, in the short, medium, and long term. Major uncertainties exist in the projections due to the scale and scope of the studies. Most studies estimated the future global annual demand for these four metals as an ascending trend in the short and medium term. Some studies found that the annual metal demand would peak between 2030 and 2050 due to the saturation of the automotive market or technological advances in material use. In any case, the annual demand would far exceed the production capacity in 2021. Then we compared the forecasted short-, medium-, and long-term cumulative demand for these four metals with their reserves in 2021. We found that reserves for those metals could meet the short- and medium-term requirement regarding global transportation electrification but are not likely sufficient for the long-term demand.

- Summary of proposed policies

The screened studies have proposed relevant policies to ensure future metal supply. Those policies can be generally divided into four types: (i) technology-oriented, (ii) supply-oriented, (iii) demand-oriented, and (iv) regulation-oriented. We further divided those policies into nine categories: policies related to (i) mining, (ii) research & development, (iii) manufacture, (iv) sale, (v) use, (vi) EoL treatment, (vii) international trade, (viii) organization & cooperation, (ix) standardization & regulation. This policy summary could provide enlightenment and reference to make policy interventions to secure the future critical metal supply.

From the review and analysis of relevant studies, we further discuss the following four issues: environmental and social implications of deploying electric vehicles, whether or not to electrify heavy-duty vehicles, opportunities and challenges in recycling, and future research direction. The findings of this paper can provide insights into future MFA modeling and policy design of critical material demand and supply for the clean energy transition.

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.

Data availability

Data will be made available on request.

Acknowledgments

This work is financially supported by the National Science Foundation (NSF) under Grant No. 1643244. The author thanks Apoorv Lal, Nathan Preuss, and Rishi Kaashyap Balaji for their comments on this study.

Appendix. Supporting data and data sources

Table A1
Battery capacity of different electric vehicles.

	BEV				PHEV				FCEV/HEV			
	Min.	Ref.	Max.	Ref.	Min.	Ref.	Max.	Ref.	Min.	Ref.	Max.	Ref.
LDPV	33.00	[86]	100.00	[86]	8.00	[86]	17.00	[86]	0.40	[128]	1.60	[129]
LDCV	96.55	[85]	/	/	19.04	[85]	/	/	10.50	[130]	/	/
HDCV	516.86	[85]	1073.84	[85]	92.93	[85]	201.91	[85]	5.93	[24]	70.00	[131]
HDPV	685.29	[85]	/	/	126.64	[85]	/	/	17.00	[132]	/	/

Table A2
Fuel cell power of fuel cell electric vehicles.

	Min	Ref.	Max	Ref.
LDPV	68.57	[40]	150.48	[40]
LDCV	109.90	[40]	109.90	[40]
HDCV	92.31	[40]	343.78	[40]
HDPV	218.08	[40]	218.08	[40]

Table A3
Practical and theoretical specific energy of different batteries.

Battery	Low practical specific energy	Ref.	High practical specific energy	Ref.	Theoretical high specific energy	Ref.
MnZn	90	[133]	110	[133]	/	/
Pd-acid	38	[29]	60	[29]	/	/
NiMH	42	[29]	110	[29]	/	/
Ni-Cd	50	[134]	75	[134]	/	/
NMC	150	[135]	220	[135]	/	/
NaNiCl	80	[136]	120	[137]	/	/
NMC+	260	[138]	407	[139]	/	/
NCA	200	[135]	260	[135]	/	/
LFP	90	[135]	120	[135]	/	/
LMO	100	[135]	150	[135]	/	/
LCO	150	[135]	200	[135]	/	/
LTO	50	[135]	80	[135]	/	/
Li-S	350	[29]	600	[29]	2500	[140]
Na-S	150	[141]	450	[142]	1274	[140]
Zn-S	274	[143]	502	[144]	1083	[145]
Li-air	450	[34]	800	[29]	3458	[34]
Na-air	N/A	N/A	N/A	N/A	1683	[146]
Zn-air	180	[29]	500	[29]	1084	[147]

Table A4
Cycle life of different batteries.

Battery	Low practical specific energy	Ref.	High practical specific energy	Ref.
MnZn	20	[148]	30	[148]
Pd-acid	300	[29]	800	[29]
NiMH	600	[29]	1200	[29]
NiCd	2000	[134]	2500	[134]
NMC	1000	[135]	2000	[135]
NaNiCl	300	[149]	500	[149]
NCA	500	[135]	500	[135]
LFP	2000	[135]	2000	[135]
LMO	300	[135]	700	[135]
LCO	500	[135]	1000	[135]
LTO	3000	[135]	7000	[135]
Li-S	100	[29]	500	[29]
Na-S	2500	[141]	4500	[150]
Zn-S	N/A	N/A	N/A	N/A
Li-air	20	[29]	100	[29]
Na-air	18	[146]	100	[146]
Zn-air	150	[29]	450	[29]

Table A5
Summary of selected articles.

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
1	[151]	Global	×	2010–2100	LDV	BEV, PHEV, HEV	LIB	Li	Flow-driven	**Focus:** Demand-recycling-reserve **No policy implication**
2	[77]	Global	×	2010–2050	LDPV	FCEV	/	Pt	Linear projection	**Focus:** Recycling-demand **Policy implications:** 1. Rise recycling
3	[98]	Global	×	2000–2050	LDPV	EV	/	Al	Stock-driven	**Focus:** Recycling-demand **Policy implications:** 1. Technologies for sorting mixed aluminum scrap 2. Export of mixed scrap to developing countries, combined with manual sorting in these countries, may be a realistic intermediate solution 3. Cost-effective technologies for separating alloying elements and impurities from the aluminum melt 4. Design for disassembly and for recycling 5. Scrap recovery and sorting in nonautomotive sectors (such as buildings, cans, or appliances) has the potential to immediately reduce the amount of downgraded scrap currently being absorbed by automotive secondary castings 6. Exploring alternative applications for mixed or casting scrap 7. Mandating properties instead of the composition of aluminum alloys would 8. intelligent blending of different scrap alloys
4	[71]	Global	×	2007	N/A	EV	LIB	Li	Static	**Focus:** Recycling-demand **Policy implications:** 1. Higher resource efficiency and reduced raw material consumption
5	[83]	Global	×	2010–2100	LDPV	BEV, PHEV	LIB	Li	Stock-driven	**Focus:** Recycling-demand-production **Policy implications:** 1. Encourage recycling 2. Maintain a portfolio of known lithium resources at the feasibility stage to minimize the time of any prospective disruption 3. As well as bringing other vehicle technologies to competitive readiness
6	[72]	Global	×	2009	N/A	BEV, PHEV, HEV	LIB	Mn	Static	**Focus:** Demand No policy implication
7	[45]	Global	√	1975–2100	N/A	FCEV	/	Pt	Stock-driven	**Focus:** Demand-waste-reserve No policy implication
8	[152]	EU27	×	2010–2050	N/A	BEV, PHEV	LIB	Li	Flow-driven	**Focus:** Recycling-demand No policy implication
9	[109]	US	×	2015–2040	LDV	BEV, PHEV, HEV	LMO, LFP, LCO, NMC	Li, Ni, Fe, Co, Al, Cu, Mn, graphite, and others	Flow-driven	**Focus:** Recycling-demand **Policy implications:** 1. Cost-effective recycling
10	[153]	Europe	×	2010–2030	LDPV, LDCV, HDCV	BEV, PHEV, HEV	NCA, NMC, LFP, Li-air, Li-S	Li, Co, Mn, Ni, Fe, Al	Stock-driven	**Focus:** Demand-reserve No policy implication
11	[154]	Japan	×	2012–2050	LDPV	HEV, PHEV, BEV, and FCEV	/	Fe, Al	Flow-driven	**Focus:** Demand No policy implication
12	[155]	Japan	×	2010–2030	N/A	HEV	NiMH	REEs	Flow-driven	**Focus:** Recycling-demand No policy implication
13	[156]	Germany	×	2015–2050	N/A	BEV, PHEV, HEV	NMC, LFP	Li, Ni, Co, Cu, graphite	N/A	**Focus:** Recycling-demand No policy implication
14	[46]	Global	√	2011	N/A	EV	NCA, NMC, LCO	Ni, Co	Trade-linked static	**Focus:** Demand No policy implication
15	[39]	Japan	×	2010–2030	LDPV	HEV	NiMH	REEs	Stock-driven	**Focus:** Recycling **Policy implications:** 1. Improve the efficiency of recovery

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
16	[80]	China	×	2015–2060	N/A	EV	Lead-acid battery	Pd	2% increasing rate	**Focus:** Recycling-demand **Policy implications:** 1. Optimize lead industrial structure, like expanding lead imports by a suitable amount to make up for shortages domestically, should be an endeavor. 2. Improve the utilization technology, collection system and recycling technology towards closed-loop supply are supposed to be the most environmental-friendly and effective way to keep sustainable development.
17	[78]	Global	√	2002–2025	N/A	EV	LIB	Co	Mine production-based linear regression	**Focus:** Production-based demand No policy implication
18	[76]	China	×	2001–2013	N/A	LIB	LIB, alkaline battery	Co, Ni, Zn, Cu, Mn	Static	**Focus:** Recycling **Policy implications:** 1. Promote the creation of a better waste battery collection system 2. Incentivize resource recycling enterprise .3 Restrain the use of raw ore or penalize such uses by tighter environmental and resource restrictions to prevent recycling enterprises from obtaining more profits as a result of the use of raw ore
19	[110]	Global	×	2015–2030	LDPV	BEV, PHEV, FCV, HEV	NCA	Li	Stock-driven	**Focus:** Recycling-demand **Policy implications:** 1. A large acquisition of an EV for its own fleet eventually combined with incentives and/or regulations encouraging the local use of an EV (privileged driving areas, selection criteria for public markets and partnerships, etc.) would start a local life cycle of batteries 2. Develop secondary markets
20	[16]	Global	√	2014	LDPV, HDPV	BEV, PHEV, E-bike	LMO, LCO, LFP, NCM	Li	Trade-linked static	**Focus:** production **Policy implications:** 1. Increase primary resource supply through more intensive domestic resource mining 2. More aggressive strategy on import 3. Increase secondary resource supply through well-established recycling system.
21	[157]	Global	×	2014–2050	LDPV	PHEV, BEV, HEV	NMC, LFP, LMO	Li, Co	Flow-driven	**Focus:** Recycling-demand No policy implication
22	[58]	China	×	2015	LDPV, HDPV	PHEV, BEV, E-bike	NMC, LFP, LMO, LCO	Li	Static	**Focus:** Production- recycling-reserve **Policy implications:** 1. Enhance stockpile through imports or greater exploration and domestic mining 2. Promote recycling
23	[158]	Global	×	2010–2050	LDPV	BEV, PHEV, FCV, HEV	LIB	Cu, Co, and Li, REEs (Nd), Ta	Stock-driven	**Focus:** Demand No policy implication
24	[159]	US	×	2000–2050	LDPV	BEV, PHEV, FCV, HEV	LIB, NiMH	Fe, Al, Mg, REEs (Ce, Nd, and La)	Flow-driven	**Focus:** Recycling-demand No policy implication
25	[99]	Global	×	2010–2050	LDPV	BEV, PHEV, FCV, HEV	NMC, NCA, Li-S	Li	Stock-driven	**Focus:** Recycling-demand **Policy implications:** 1. Cost-efficient recycling 2. Functioning infrastructure must be established, requiring effective cooperation between battery researchers, battery manufacturers, and recycling companies. 3. Expanding recycling: 1) a standard configuration of batteries to develop appropriate recycling equipment; 2) further chemistry standardization to reduce the necessity for sorting; 3) labeling of cells to allow for better sorting; 4) advanced battery design for disassembly makes separation of contained materials possible

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
26	[84]	Global	×	2010–2100	LDPV	BEV, HEV, PHEV, FCEV	LFP, NMC	Li, Co, PGMs, REEs (Nd, and Dy)	Stock-driven	**Focus:** Recycling-demand **Policy implications:** 1. Higher recycling rate
27	[56]	US	×	2000–2050	LDPV	BEV, PHEV, HEV, FCEV	N/A	Batteries	Flow-driven	**Focus:** Waste generation **Policy implications:** 1. regional specific EOL management strategies, such as various densities of stock, secondary market, and existing infrastructure 2. Public sectors should make concerted efforts to facilitate partnerships to encourage the efficient reuse and recycling of retired EV batteries
28	[96]	China	×	2018–2030	LDPV	BEV, PHEV, FCV, HEV	NiMH, LIB	REEs: La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Y, and *Sc*	Stock-driven	**Focus:** Recycling-demand **Policy implications:** 1. Promote recovery technologies 2. Material substitution 3. Discovery and exploitation of new mines
29	[115]	China	×	2000–2050	N/A	EV	LIB	Li	Flow-driven	**Focus:** Recycling-demand **Policy implications:** 1. Another option is to change the domestic production structure to distribute import amounts more becomingly. The approaches to reach this aim include scaling up the mining output and slowing down the expansion of downstream capacity. 2. encourage EV companies to import chemicals and batteries by adjusting import tariffs.
30	[111]	EU	×	2005–2030	LDPV	BEV, PHEV	NMC, NCA	Co, Li	Flow-driven	**Focus:** Recycling-reuse-demand **Policy implications:** 1. bans of some specific LIB chemistry or substance 2. minimum recycling content, re-use targets
31	[59]	Global	√	2010–2050	LDPV, LDCV, HDPV, HDCV	BEV, HEV, FCEV, PHEV, E-2/3wheeler	NMC	Li	Stock-driven	**Focus:** Demand-reserve-production **Policy implications:** 1. Supply chain network for electric vehicle batteries that will consider remanufacturing and recycling infrastructures
32	[73]	China	×	2016	N/A	BEV, HEV, PHEV, E-bike	LFP, NCA, NMC, LCO, LMO	LI, Co, Ni, Graphite	Static	**Focus:** Recycling-demand **Policy implications:** 1. EoL LIB waste management system
33	[79]	Global	×	1970–2030	N/A	PHEV	NMC, NCA, LMO, LFP	Graphite, Li, Co, and REEs (Dy, Tb, Pr, and Nd)	Sale growth rate	**Focus:** Demand No policy implication
34	[85]	Global	×	2000–2100	LDPV, LDCV, HDPV, HDCV	BEV, PHEV	NMC	Li	Flow-driven	**Focus:** Demand-recycling **Policy implications:** Carefully consider the electrification in the heavy-duty segment
35	[40]	Global	×	2000–2100	LDPV, LDCV, HDPV, HDCV	FCEV	/	PGMs	Flow-driven	**Focus:** Demand-recycling-reserve **Policy implications:** 1. Reducing PGM loading of fuel cells; a standard for PGM loading level as the market entry requirement for new FCV models 2. Increase PGM recycling rates, 3. Improving the reliability of the PGM supply chain 4. To further promote fuel cell technology development, joint efforts from the government, automotive industry, and the research community are necessary so that more R&D funding will be available for lowering PGM loading of fuel cells 5. Subsidy or tax exemption for the purchase of FCEVs should be offered to encourage the low-PGM loading of FCEVs. Technology

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
										6. Technology sharing and transfer from the technology-leading countries and enterprises to their counterparts in the developing world is also needed 7. Improve PGM recycling from EoL vehicles 8. Greater R&D efforts are also needed to improve the efficiency of recycling technology while reducing recycling costs. 9. International cooperation on ELV management should be in place 10. A more robust trading network be developed with these countries: joint resource development 11. Ambitious FCV deployment plans to establish a certain scale of PGM stockpile to avoid the negative impacts from possible supply fluctuation
36	[70]	Global	×	2015–2050	N/A	BEV, PHEV, HEV, FCEV	LIB	Li, Ni, Co, Cu, Al, Fe, Pt, and others	Stock -driven	**Focus:** Demand-recycle **Policy implications:** 1. Recycling could be explored based on the potential environmental implications as well as the absolute quantities. 2. Develop product designs and decomposition technologies that make it possible to recycle while keeping the original material or component quality, rather than minor components being lost in the slag or larger metal streams due to the increased miniaturization and complexity of parts.
37	[104]	Global	×	2015–2050	LDPV	BEV, PHEV, HEV	LIB	Li	Flow-driven	Focus: Demand-recycle 1. Do not rush into EoL recycling of lithium-ion batteries has limited impacts on short/medium-term 2. Improvements in the loss in the manufacturing phases through recovering process scrap 3. Promote car-sharing
38	[160]	Global	×	2019–2025	N/A	EV	LIB	Li	Stock -driven	**Focus:** Demand No policy implication
39	[161]	EU	×	2010–2050	N/A	BEV, PHEV	NMC, NCA, LCO	Li, Ni	Flow-driven	**Focus:** Demand-recycling-reuse No policy implication
40	[82]	Global	×	2015–2050	LDPV	BEV, PHEV, HEV	NCA, LMO, NiMH	Al, Co, Cu, Fe, Li, Mn, Ni, REEs (Nd, and Dy)	Stock-driven	**Focus:** Demand-reserve-recycling **Policy implications:** 1. Exploring the feasibility of product design substitution is important when assessing the vulnerability to supply risk dimension: Due to the fact that nickel-based batteries are mostly used in HEVs today, the possible future mix of lithium and nickel-based batteries
41	[92]	China	×	2015–2050	LDV	BEV, PHEV, HEV	NiMH, NCA, LFP, LMO, NCM	Graphite, Fe, Mn, Ti, Al, Cu, Ni, Co, Li, B, REEs (La, Ce, Pr, Sm, Dy, and Nd)	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. Balance the development and use of different types of batteries 2. Increase resources efficiency 3. Secure the availability of Ni, Co, and Cu from outside the country 4. Increase the collection and processing of end of life EVs and their batteries 5. Increase the production of several metals
42	[55]	Fujian, China	×	2010–2050	LDPV	EV	N/A	Cu	Flow-driven	**Focus:** Demand **Policy implications:** 1. Strengthen recycling 2. Adopt a circular design 3. Reduce and reuse scrap 4. Improve copper use technology 5. Extend the service life of products 6. Improve power transmission and 7. Distribution efficiency of the grid 8. Material substitution

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
43	[86]	Global	×	2005–2050	LDPV	BEV, PHEV	NMC, NCA, LFP, Li-air, Li-S	Li, Ni, Co, Mn, Al, Cu, graphite	Stock -driven	**Focus:** Demand-recycling-reuse **Policy implications:** Promoting recycling
44	[66]	China	√	2010–2036	LDCV, LDPV, HDC	BEV, PHEV, HEV	NMC, NCA, Li-S, LFP	Waste LIBs	Flow-driven	**Focus:** Recycling-reuse **Policy implications:** 1. Standardized management recycling 2. Safety certificate for 2nd use 3. Cost of recovery 4. Plan on the number of collection stations
45	[60]	China	×	2006–2015	LDPV, HDPV	BEV, PHEV, E-bike	NCM, NCA, LCO	Co	Static	**Focus:** Demand-recycling **Policy implications:** 1. Improve the recovery rate 2. Technological development of the economic and efficient enrichment processes 3. Alternative material
46	[53]	Global	√	2015–2030	LDPV, LDCV, HDPV, HDCV	HEV, BEV, PHEV, FCEV,	LFP, NMC, LMO, NCA	AL, Co, Cr, Cu, Fe, Li, Mn, Ni	Stock-driven	**Focus:** Demand **Policy implications:** 1. Improve treatment methods 2. Technological break for new material
47	[74]	EU	×	2017–2050	LDPV	BEV, PHEV	NMC, NCA, LMO	Co	Static, and flow-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Efficient recycling system 2. Enhance collection rates 3. Encourage increased accountability and traceability of EoL vehicle 4. Create favorable market conditions for the emergence of new business models 5. New Battery design and technology 6. Alternative material
48	[103]	Europe	×	2020–2040	LDPV, LDCV	BEV, PHEV	NMC, NCA	Li, Co, Ni, Cu, graphite	Flow-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Use of Advanced and Beyond lithium-ion technologies 2. Promote recycling and 2nd 3. Avoid a surplus of secondary supply and consider open-loop recycling
49	[93]	Global	×	2020–2050	N/A	BEV, PHEV, HEV	NiMH	REEs: Nd, Dy, Pr, and Tb	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. Reduce metals demand, 2. Increase other coproduced metals demand 3. Increase supply from target metals-rich deposits 4. Enhance the supply of REE from ores with different REEs distribution 5. Increase metals recycling, as reuse and remanufacturing
50	[61]	China	×	2000–2030	N/A	BEV, PHEV, E-bike	NMC, LMO, LFP, LCO	Li	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Promote the technology on LIBs recycling and 2. Promote salt lake exploitation 3. Specific laws or regulations on obsolete LIBs recycling 4. Use alternative resources
51	[52]	Global	√	2020–2040	LDV	BEV, PHEV	LCO, LMO, NCA, LFP	Li, Co, Ni, Mn	Flow-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Adopt lower-cobalt chemistries 2. Promote recycling 3. Develop manufacturing 4. Market-driven recycling industry
52	[107]	UK	×	2020–2050	LDCV, LDPV	EV	NMC, NCA, LFP	Li, Ni, Mn. Co	Flow-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Promote collection and recycling, and reuse 2. Shift to a shared mobility mode
53	[69]	Global	×	2015–2030	N/A	BEV, HEV, FCEV	LIB, lead-acid battery	Total material requirement	Flow-driven	**Focus:** Demand **Policy implications:** 1. Promote recycling

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
54	[62]	China	×	2000–2018	LDPV, HDPV	BEV, PHEV, E-tricycle, E-bicycle	LIB	Li, Co	Static	**Focus:** Demand-recycling **Policy implications:** 1. Encourage the innovation of lithium-ion battery technology 2. Strengthen closed-loop recycling 3. Promote echelon utilization 2nd
55	[87]	Global	×	2020–2040	PV	PHEV, BEV	NMC, NCA	Co, Cu, Ni	Flow-driven	**Focus:** Demand-recycle **Policy implications:** 1. Battery lifetime extension 2. Increase the recycling efficiency
56	[101]	NL	×	2010–2050	LDPV	PHEV, HEV, BEV	LMO, NMC, NCA	Li, Co, Ni	Flow-driven	**Focus:** Demand **Policy implications:** 1. Establish a comprehensive system for tracking and collecting EV waste 2. Efficient EoL battery management systems and recycling infrastructure also need to be well established 3. Battery design using Ni to replace Co
57	[112]	China	×	2009–2030	Commercial passenger	HEV, PHEV, BEV	NMC, LFP, LMO	Fe, Al, Cu, Mn, Co, Ni	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Promote recycling
58	[65]	Ireland	×	2010–2050	Passenger	HEV, PHEV, BEV	N/A	LIB	Flow-driven	**Focus:** Demand-reuse **Policy implications:** 1. Business models could be created to promote reuse
59	[113]	Norway	×	2011–2030	LDPV	BEV	LMO, NMC, NCA, LFP	Battery	Stock-driven	**Focus:** Demand-waste generation **Policy implications:** 1. Adapt to changing battery types and sizes of the retired batteries for reuse and recycling cross regions
60	[108]	US	×	2000–2050	LDPV, LDCV	HEV, BEV, PHEV	LIB, Li-S, Li-air	Li	Flow-driven	**Focus:** Demand-recycle-reserve **Policy implications:** 1. Promote collection network 2. Promote recycling and reuse
61	[57]	Vienna, Austria	×	2020–2050	LDPV, LDCV, HDPV, HDCV	FCEV, BEV, HEV E-scooter, E-bike	N/A	All materials for vehicles	Stock-driven	**Focus:** Demand **Policy implications:** 1. Promote public transport 2. Establish a collection system for EoL vehicles 3. Promote recycling
62	[94]	China	×	2020–2050	LDPV	PHEV, BEV	NMC,	Li, Ni, Co	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Promote recycling 2. Enhance self-sufficiency in battery raw materials supply
63	[100]	Brazil	×	2020–2030	LDPV	BEV, PHEV	NMC, NCA	Li, Co, Ni, Mn, graphite	Stock-driven	**Focus:** Demand-recycling-reserve **Policy implications:** 1. Remanufacture and/or repurpose EOL LIBs prior to recycling 2. Improve Battery design for recovery 3. Technological development and cost-effectiveness for recycling
64	[102]	China	×	2010–2050	LDPV, HDPV	FCV, HEV, BEV, PHEV	NMC, Li-air, NCA, Li-S	Li	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Low-lithium cathode material batteries 2. Battery lifetime extension 3. Promote second-use 4. Alternative material for lithium-free battery 5. Co-operation among consumers, enterprises, and the government is needed to improve the recovery rate of EoL batteries. 6. Accelerate the formulation of relevant recycling standards 7. Improve the recycling rate 8. Ensure the quality of recycled material 9. Cost-effective recycling
65	[97]	Global	×	2010–2050	LDPV, LDCV, HDPV, HDCV	FCEV	N/A	Pt	Stock-driven	**Focus:** Demand-recycling-reserve-production **Policy implications:** 1. Incentives and laws for recycling 2. Exploit new platinum resources

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
66	[75]	UK	×	2017	LDPV	BEV, PHEV	LIB	Co	Static	**Focus:** Demand No policy implication
67	[51]	Global	√	2020–2050	LDPV, HDPV	BEV, PHEV	NMC, NCA, LFP, LMO, Li-S, Li-air	Co	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Low- cobalt and cobalt-free technologies 2. Technological development for the recycling 3. Extended producer responsibility system and design for remanufacturing, reuse, and recycling 4. Better societal collection and recycling system 5. Relevant regulations and industrial standards 6. Enhance the exploration of cobalt deposits and deep-sea mining enabled by advanced extraction technologies and improve the efficiency of ore extraction, smelting, and refining
68	[95]	China	×	2005–2050	LDPV	BEV, PHEV, FCEV	LFP, NMC	Li, Co, Ni	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Promote the lithium supply, including expanding the domestic production capacity from salt lake brine and seawater, and secure the import source 2. Promote recycling 3. Consider developing FCEV
69	[50]	Global	√	2020–2050	LDPV	BEV, FCEV	/	PGMs	Stock-driven	**Focus:** Demand **Policy implications:** 1. Technological and efficient recycling 2. Extended producer responsibility: design 3. Regulation on limiting disposal 4. Mobility as a Service 5. Alternative material
70	[88]	Global	×	2020–2035	N/A	BEV, PHEV, FCEV	NMC, NCA	Li, Ni, Co, Mn	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. Adopt highly efficient battery recycling 2. Promote technological development in battery 3. Investigate the relationship between recycling and reuse 4. Upscale recycling
71	[64]	UK	×	2030–2040	LDPV, LDCV	BEV, PHEV	NMC, NCA, LMO	Battery	Flow-driven	**Focus:** Demand-recycling **Policy implications:** 1. Advanced recycling: direct recycling and biological processing methods 2. Automation in sorting and dissembling batteries
72	[63]	EU	×	2016	LDPV	PHEV, BEV, HEV, E-bike	NMC, NCA, LCO, LMO, LFP	Co, Li, Mn, graphite, Ni	Static	**Focus:** Demand-recycling **Policy implications:** 1. Interconnections between different materials in all the lifecycle stages 2. Quantification of the competition for raw materials using other applications detailed in the individual raw materials 3. Develop efficient collection strategies 4. Importance of developing targeted recycling strategies 5. Information on the composition of stocks for LIB 6. Information on the composition of the trade flows is also key for trade agreements
73	[68]	China	×	2020–2050	LDPV	BEV, PHEV, HEV	LIB	All materials	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. recycling for coping with oversupply 2. promoting cascading use

(*continued on next page*)

Table A5 (*continued*)

	Literature	Scope	Regional specific	Period	Sector	Vehicle	Battery	Material	MFA model	Remark
74	[54]	Catalonia, Spain	×	2020–2050	LDPV	BEV, HEV, PHEV	LIB	Co, Cu, Li, Ni	Flow-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. EV sales targets combined with the recycling efficiency and secondary material use target 2. Promoter recycling efficiency obligations and targets 3. Extended producer responsibility on new batteries to ensure their collection and to proceed in the repurposing for a second use 4. Eco-design of the EV battery for repairing, repurposing and recycling, reuse
75	[114]	Thailand	×	2019–2048	LDPV	HEV, PHEV	NiMH	Ni	Stock-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Upscale recycling and reuse
76	[49]	Global	√	2015–2050	N/A	BEV, PHEV, HEV	N/A	Cu	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. Adopt alternative materials 2. Improve the recovery rate 3. Efficient production
77	[105]	Sweden	×	2020–2050	LDPV	BEV, PHEV	NMC, Li-air, Li-S	Li, Ni, Cu, Co, Mn, graphite	Stock-driven	**Focus:** Demand-recycling **Policy implications:** 1. Promote effective recycling and collection 2. Better traceability over battery lifetimes 3. Standardize the design, transport, handling, and recycling of EV batteries 4. Cost-effective recycling technologies 5. Innovative business models 6. Regulatory framework for reuse 7. Share mobility and public transport
78	[106]	China, and the U.S.	×	2021–2030	LDPV	BEV	NMC, NCA, LMO, LFP	Li, Ni, Co, Cu, Graphite	Stock-driven	**Focus:** Demand-recycling-reuse **Policy implications:** 1. Consider reuse as an optimal option 2. Adopt FCEV 3. Improve the waste management system

References

[1] IEA. Net zero by 2050-a roadmap for the global energy sector. 2021.
[2] IEA. World Energy Outlook 2021. 2021.
[3] Plötz P. Hydrogen technology is unlikely to play a major role in sustainable road transport. Nat Electron 2022;5:8–10. doi:10.1038/s41928-021-00706-6.
[4] IEA. Global CO2 emissions in transport by mode in the Sustainable Development Scenario, 2000-2070. 2022.
[5] Tran M, Banister D, Bishop JDK, McCulloch MD. Realizing the electric-vehicle revolution. Nat Clim Chang 2012;2:328–33. doi:10.1038/nclimate1429.
[6] Melton N, Axsen J, Sperling D. Moving beyond alternative fuel hype to decarbonize transportation. Nat Energy 2016;1:1–10. doi:10.1038/nenergy.2016.13.
[7] Crabtree G. The coming electric vehicle transformation. Science (80-) 2019;366:422–4. doi:10.1126/science.aax0704.
[8] IEA. Technology roadmap: hydrogen and fuel cells. 2015.
[9] Bloomberg. Energy transition investment trends 2022. 2022.
[10] Watari T, Nansai K, Nakajima K. Review of critical metal dynamics to 2050 for 48 elements. Resour Conserv Recycl 2020;155:104669. doi:10.1016/j.resconrec.2019.104669.
[11] IEA. The role of critical minerals in clean energy transitions. 2022. https://doi.org/10.1787/f262b91c-en.
[12] IEA. Global EV Outlook 2022: securing supplies for an electric future 2022.
[13] Brunner P.H., Rechberger H. Practical handbook of material flow analysis. Washington DC: 2004. https://doi.org/10.1007/bf02979426.
[14] Pauliuk S, Arvesen A, Stadler K, Hertwich EG. Industrial ecology in integrated assessment models. Nat Clim Chang 2017;7:13–20. doi:10.1038/nclimate3148.
[15] Nansai K, Nakajima K, Kagawa S, Kondo Y, Shigetomi Y, Suh S. Global mining risk footprint of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum in Japan. Environ Sci Technol 2015;49:2022–31. doi:10.1021/es504255r.
[16] Sun X, Hao H, Zhao F, Liu Z. Tracing global lithium flow: a trade-linked material flow analysis. Resour Conserv Recycl 2017;124:50–61. doi:10.1016/j.resconrec.2017.04.012.
[17] Sverdrup HU, Ragnarsdottir KV. A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use. Resour Conserv Recycl 2016;114:130–52. doi:10.1016/j.resconrec.2016.07.011.
[18] van der Voet E. Substances from cradle to grave: development of a methodology for the analysis of substance flows through the economy and the environment of a region. Leiden University; 1996.
[19] Müller E, Hilty LM, Widmer R, Schluep M, Faulstich M. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ Sci Technol 2014;48:2102–13. doi:10.1021/es403506a.
[20] Baccini P, Bader H-P. Regionaler stoffhaushalt: erfassung, bewertung und steuerung. Heidelberg: Spektrum Akademischer Verlag; 1996.
[21] Liu G, Müller DB. Centennial evolution of aluminum in-use stocks on our aluminized planet. Environ Sci Technol 2013;47:4882–8. doi:10.1021/es305108p.
[22] Augiseau V, Barles S. Studying construction materials flows and stock: a review. Resour Conserv Recycl 2017;123:153–64. doi:10.1016/j.resconrec.2016.09.002.
[23] Lie TT, Prasad K, Ding N. The electric vehicle: a review. Int J Electr Hybrid Veh 2017;9:49. doi:10.1504/IJEHV.2017.10003709.
[24] ANL. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. 2021. https://doi.org/10.11578/GREET-Excel-2021/dc.20210902.1.
[25] Caspeta L, Buijs NAA, Nielsen J. The role of biofuels in the future energy supply. Energy Environ Sci 2013;6:1077–82. doi:10.1039/c3ee24403b.
[26] Yong JY, Ramachandaramurthy VK, Tan KM, Mithulananthan N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. Renew Sustain Energy Rev 2015;49:365–85. doi:10.1016/j.rser.2015.04.130.
[27] Jeff Desjardins. The Evolution of Battery Technology 2016. https://www.visualcapitalist.com/evolution-of-battery-technology/.
[28] TVA. Batteries for Electric Vehicles 2022. https://www.tva.com/energy/technology-innovation/batteries-for-electric-vehicles#:~:text=Nickel cadmium batteries%2C once commonly,still use nickel cadmium batteries.
[29] Cano ZP, Banham D, Ye S, Hintennach A, Lu J, Fowler M, et al. Batteries and fuel cells for emerging electric vehicle markets. Nat Energy 2018;3:279–89. doi:10.1038/s41560-018-0108-1.
[30] Zhao S, You F. Comparative life-cycle assessment of li-ion batteries through process-based and integrated hybrid approaches. ACS Sustain Chem Eng 2019;7:5082–94. doi:10.1021/acssuschemeng.8b05902.
[31] Beuse M, Steffen B, Schmidt TS. Projecting the competition between energy-storage technologies in the electricity sector. Joule 2020;4:2162–84. doi:10.1016/j.joule.2020.07.017.
[32] Ziv B, Borgel V, Aurbach D, Kim J-H, Xiao X, Powell BR. Investigation of the reasons for capacity fading in li-ion battery cells. J Electrochem Soc 2014;161:A1672–80. doi:10.1149/2.0731410jes.
[33] Choi JW, Aurbach D. Promise and reality of post-lithium-ion batteries with high energy densities. Nat Rev Mater 2016;1:16013. doi:10.1038/natrevmats.2016.13.
[34] Luntz AC, McCloskey BD. Nonaqueous Li–Air Batteries: a Status Report. Chem Rev 2014;114:11721–50. doi:10.1021/cr500054y.
[35] Sharaf OZ, Orhan MF. An overview of fuel cell technology: fundamentals and applications. Renew Sustain Energy Rev 2014;32:810–53. doi:10.1016/j.rser.2014.01.012.
[36] NACFE. Making sense of heavy-duty hydrogen fuel cell tractors. 2020.
[37] US DOE. Hydrogen strategy: enabling A low-carbon economy. 2020.
[38] Nationalgrid. The hydrogen colour spectrum 2022. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum#:~:text=Turquoise hydrogen is made using,being permanently stored or used.
[39] Xu G, Yano J, Sakai S ichi. Scenario analysis for recovery of rare earth elements from end-of-life vehicles. J Mater Cycles Waste Manag 2016;18:469–82. doi:10.1007/s10163-016-0487-y.
[40] Hao H, Geng Y, Tate JE, Liu F, Sun X, Mu Z, et al. Securing Platinum-Group Metals for Transport Low-Carbon Transition. One Earth 2019;1:117–25. doi:10.1016/j.oneear.2019.08.012.
[41] IEA. Global EV Outlook 2021: accelerating ambitions despite the pandemic. 2021.
[42] USGS. Mineral commodity summaries 2022. 2022.
[43] IPCC. IPCC Special report on the impacts of global warming of 1.5°C. 2018.
[44] IPCC. IPCC Sixth assessment report. 2022.
[45] Elshkaki A. An analysis of future platinum resources, emissions and waste streams using a system dynamic model of its intentional and non-intentional flows and stocks. Resour Policy 2013;38:241–51. doi:10.1016/j.resourpol.2013.04.002.
[46] Schmidt T, Buchert M, Schebek L. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resour Conserv Recycl 2016;112:107–22. doi:10.1016/j.resconrec.2016.04.017.
[47] Raabe D, Tasan CC, Olivetti EA. Strategies for improving the sustainability of structural metals. NatureNature 2019;575:64–74. doi:10.1038/s41586-019-1702-5.
[48] Tierney J. The reign of recycling. New York Times; 2015 https://www.nytimes.com/2015/10/04/opinion/sunday/the-reign-of-recycling.html (accessed June 4, 2020).
[49] Watari T, Northey S, Giurco D, Hata S, Yokoi R, Nansai K, et al. Global copper cycles and greenhouse gas emissions in a 1.5°C world. Resour Conserv Recycl 2022;179:106118. doi:10.1016/j.resconrec.2021.106118.
[50] Tong X, Dai H, Lu P, Zhang A, Ma T. Saving global platinum demand while achieving carbon neutrality in the passenger transport sector: linking material flow analysis with integrated assessment model. Resour Conserv Recycl 2022;179:106110. doi:10.1016/j.resconrec.2021.106110.
[51] Zeng A, Chen W, Rasmussen KD, Zhu X, Lundhaug M, Müller DB, et al. Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. Nat Commun 2022;13:1341. doi:10.1038/s41467-022-29022-z.
[52] Dunn J, Slattery M, Kendall A, Ambrose H, Shen S. Circularity of Lithium-Ion Battery Materials in Electric Vehicles. Environ Sci Technol 2021;55:5189–98. doi:10.1021/acs.est.0c07030.
[53] Jones B, Elliott RJR, Nguyen-Tien V. The EV revolution: the road ahead for critical raw materials demand. Appl Energy 2020;280:115072. doi:10.1016/j.apenergy.2020.115072.
[54] Crespo MS, González MVG, Peiró LT. Prospects on end of life electric vehicle batteries through 2050 in Catalonia. Resour Conserv Recycl 2022;180. doi:10.1016/j.resconrec.2021.106133.
[55] Huang CL, Xu M, Cui S, Li Z, Fang H, Wang P. Copper-induced ripple effects by the expanding electric vehicle fleet: a crisis or an opportunity. Resour Conserv Recycl 2020;161. doi:10.1016/j.resconrec.2020.104861.
[56] Ai N, Zheng J, Chen WQ. U.S. end-of-life electric vehicle batteries: dynamic inventory modeling and spatial analysis for regional solutions. Resour Conserv Recycl 2019;145:208–19. doi:10.1016/j.resconrec.2019.01.021.
[57] Gassner A, Lederer J, Kovacic G, Mollay U, Schremmer C, Fellner J. Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna. J Clean Prod 2021;311:127591. doi:10.1016/j.jclepro.2021.127591.
[58] Hao H, Liu Z, Zhao F, Geng Y, Sarkis J. Material flow analysis of lithium in China. Resour Policy 2017;51:100–6. doi:10.1016/j.resourpol.2016.12.005.
[59] Hache E, Seck GS, Simoen M, Bonnet C, Carcanague S. Critical raw materials and transportation sector electrification: a detailed bottom-up analysis in world transport. Appl Energy 2019;240:6–25. doi:10.1016/j.apenergy.2019.02.057.
[60] Chen Z, Zhang L, Xu Z. Analysis of cobalt flows in mainland China: exploring the potential opportunities for improving resource efficiency and supply security. J Clean Prod 2020;275:122841. doi:10.1016/j.jclepro.2020.122841.
[61] Guo X, Zhang J, Tian Q. Modeling the potential impact of future lithium recycling on lithium demand in China: a dynamic SFA approach. Renew Sustain Energy Rev 2021;137:110461. doi:10.1016/j.rser.2020.110461.
[62] Liu W, Liu W, Li X, Liu Y, Ogunmoroti AE, Li M, et al. Dynamic material flow analysis of critical metals for lithium-ion battery system in China from 2000 to 2018. Resour Conserv Recycl 2021;164:105122. doi:10.1016/j.resconrec.2020.105122.
[63] Matos CT, Mathieux F, Ciacci L, Lundhaug MC, León MFG, Müller DB, et al. Material system analysis: a novel multilayer system approach to correlate EU flows and stocks of Li-ion batteries and their raw materials. J Ind Ecol 2022;26:1261–76. doi:10.1111/jiec.13244.
[64] Nguyen-Tien V, Dai Q, Harper GDJ, Anderson PA, Elliott RJR. Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy. Appl Energy 2022;321:119230. doi:10.1016/j.apenergy.2022.119230.
[65] Fallah N, Fitzpatrick C, Killian S, Johnson M. End-of-Life Electric Vehicle Battery Stock Estimation in Ireland through Integrated Energy and Circular Economy Modelling. Resour Conserv Recycl 2021;174:105753. doi:10.1016/j.resconrec.2021.105753.
[66] Wu Y, Yang L, Tian X, Li Y, Zuo T. Temporal and spatial analysis for end-of-life power batteries from electric vehicles in China. Resour Conserv Recycl 2020;155:104651. doi:10.1016/j.resconrec.2019.104651.
[67] Gassner A, Lederer J, Fellner J. Material stock development of the transport sector in the city of Vienna. J Ind Ecol 2020:jiec.13024. doi:10.1111/jiec.13024.

[68] Chen W, Sun X, Liu L, Liu X, Zhang R, Zhang S, et al. Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions. One Earth 2022;5:875–91. doi:10.1016/j.oneear.2022.07.005.

[69] Kosai S, Matsui K, Matsubae K, Yamasue E, Nagasaka T. Natural resource use of gasoline, hybrid, electric and fuel cell vehicles considering land disturbances. Resour Conserv Recycl 2021;166:105256. doi:10.1016/j.resconrec.2020.105256.

[70] Watari T, McLellan BC, Giurco D, Dominish E, Yamasue E, Nansai K. Total material requirement for the global energy transition to 2050: a focus on transport and electricity. Resour Conserv Recycl 2019;148:91–103. doi:10.1016/j.resconrec.2019.05.015.

[71] Ziemann S, Weil M, Schebek L. Tracing the fate of lithium - The development of a material flow model. Resour Conserv Recycl 2012;63:26–34. doi:10.1016/j.resconrec.2012.04.002.

[72] Ziemann S, Grunwald A, Schebek L, Müller DB, Weil M. The future of mobility and its critical raw materials. Rev Metall Cah D'Informations Tech 2013;110:47–54. doi:10.1051/metal/2013052.

[73] Song J, Yan W, Cao H, Song Q, Ding H, Lv Z, et al. Material flow analysis on critical raw materials of lithium-ion batteries in China. J Clean Prod 2019;215:570–81. doi:10.1016/j.jclepro.2019.01.081.

[74] Baars J, Domenech T, Bleischwitz R, Melin HE, Heidrich O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat Sustain 2021;4:71–9. doi:10.1038/s41893-020-00607-0.

[75] Heidrich O, Ford AC, Dawson RJ, Manning DAC, Mohareb E, Raugei M, et al. LAYERS: a Decision-Support Tool to Illustrate and Assess the Supply and Value Chain for the Energy Transition. Sustain 2022;14:1–19. doi:10.3390/su14127120.

[76] Song X, Hu S, Chen D, Zhu B. Estimation of Waste Battery Generation and Analysis of the Waste Battery Recycling System in China. J Ind Ecol 2017;21:57–69. doi:10.1111/jiec.12407.

[77] Sun Y, Delucchi M, Ogden J. The impact of widespread deployment of fuel cell vehicles on platinum demand and price. Int J Hydrogen Energy 2011;36:11116–27. doi:10.1016/j.ijhydene.2011.05.157.

[78] Olivetti EA, Ceder G, Gaustad GG, Fu X. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule 2017;1:229–43. doi:10.1016/j.joule.2017.08.019.

[79] Ballinger B, Stringer M, Schmeda-Lopez DR, Kefford B, Parkinson B, Greig C, et al. The vulnerability of electric vehicle deployment to critical mineral supply. Appl Energy 2019;255:113844. doi:10.1016/j.apenergy.2019.113844.

[80] Sun L, Zhang C, Li J, Zeng X. Assessing the sustainability of lead utilization in China. J Environ Manage 2016;183:275–9. doi:10.1016/j.jenvman.2016.05.063.

[81] Statista. Distribution of lithium end-usage worldwide in 2021, by area of application 2022. https://www.statista.com/statistics/268787/lithium-usage-in-the-world-market/ (accessed October 18, 2022).

[82] Habib K, Hansdóttir ST, Habib H. Critical metals for electromobility: global demand scenarios for passenger vehicles, 2015–2050. Resour Conserv Recycl 2020;154:104603. doi:10.1016/j.resconrec.2019.104603.

[83] Kushnir D, Sandén BA. The time dimension and lithium resource constraints for electric vehicles. Resour Policy 2012;37:93–103. doi:10.1016/j.resourpol.2011.11.003.

[84] Harvey LDD. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. Appl Energy 2018;212:663–79. doi:10.1016/j.apenergy.2017.11.074.

[85] Hao H, Geng Y, Tate JE, Liu F, Chen K, Sun X, et al. Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment. Nat Commun 2019;10:5398. doi:10.1038/s41467-019-13400-1.

[86] Xu C, Dai Q, Gaines L, Hu M, Tukker A, Steubing B. Future material demand for automotive lithium-based batteries. Commun Mater 2020;1:99. doi:10.1038/s43246-020-00095-x.

[87] Nguyen RT, Eggert RG, Severson MH, Anderson CG. Global electrification of vehicles and intertwined material supply chains of Cobalt, Copper and Nickel. Resour Conserv Recycl 2021;167:105198. doi:10.1016/j.resconrec.2020.105198.

[88] Neidhardt M, Mas-Peiro J, Schulz-Moenninghoff M, Pou JO, Gonzalez-Olmos R, Kwade A, et al. Forecasting the global battery material flow: analyzing the break-even points at which secondary battery raw materials can substitute primary materials in the battery production. Appl Sci 2022;12. doi:10.3390/app12094790.

[89] Nickel Institute. About nickel 2022. https://nickelinstitute.org/en/about-nickel-and-its-applications/ (accessed October 18, 2022).

[90] Statista. Distribution of cobalt demand worldwide from 2010 to 2025, by end use 2022. https://www.statista.com/statistics/875803/cobalt-demand-share-end-use-worldwide/ (accessed October 18, 2022).

[91] CMP Group. Platinum Industrial Demand 2020. https://www.cmegroup.com/education/articles-and-reports/platinum-industrial-demand.html (accessed October 18, 2022).

[92] Elshkaki A. Long-term analysis of critical materials in future vehicles electrification in China and their national and global implications. Energy 2020;202:117697. doi:10.1016/j.energy.2020.117697.

[93] Elshkaki A. Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature. Commun Earth Environ 2021;2:186. doi:10.1038/s43247-021-00262-z.

[94] Ou S, Hsieh I-YL, He X, Lin Z, Yu R, Zhou Y, et al. China's vehicle electrification impacts on sales, fuel use, and battery material demand through 2050: optimizing consumer and industry decisions. IScience 2021;24:103375. doi:10.1016/j.isci.2021.103375.

[95] Liu B, Zhang Q, Liu J, Hao Y, Tang Y, Li Y. The impacts of critical metal shortage on China's electric vehicle industry development and countermeasure policies. Energy 2022;248:123646. doi:10.1016/j.energy.2022.123646.

[96] Li X, Ge J, Chen W, Wang P. Scenarios of rare earth elements demand driven by automotive electrification in China: 2018–2030. Resour Conserv Recycl 2019;145:322–31. doi:10.1016/j.resconrec.2019.02.003.

[97] Reverdiau G, Le Duigou A, Alleau T, Aribart T, Dugast C, Priem T. Will there be enough platinum for a large deployment of fuel cell electric vehicles? Int J Hydrogen Energy 2021;46:39195–207. doi:10.1016/j.ijhydene.2021.09.149.

[98] Modaresi R, Müller DB. The role of automobiles for the future of aluminum recycling. Environ Sci Technol 2012;46:8587–94. doi:10.1021/es300648w.

[99] Ziemann S, Müller DB, Schebek L, Weil M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach. Resour Conserv Recycl 2018;133:76–85. doi:10.1016/j.resconrec.2018.01.031.

[100] Castro FD, Cutaia L, Vaccari M. End-of-life automotive lithium-ion batteries (LIBs) in Brazil: prediction of flows and revenues by 2030. Resour Conserv Recycl 2021;169:105522. doi:10.1016/j.resconrec.2021.105522.

[101] Tang C, Sprecher B, Tukker A, Mogollón JM. The impact of climate policy implementation on lithium, cobalt and nickel demand: the case of the Dutch automotive sector up to 2040. Resour Policy 2021;74. doi:10.1016/j.resourpol.2021.102351.

[102] Qiao D, Wang G, Gao T, Wen B, Dai T. Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050. Sci Total Environ 2021;764:142835. doi:10.1016/j.scitotenv.2020.142835.

[103] Abdelbaky M, Peeters JR, Dewulf W. On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe. Waste Manag 2021;125:1–9. doi:10.1016/j.wasman.2021.02.032.

[104] Watari T, Nansai K, Nakajima K, McLellan BC, Dominish E, Giurco D. Integrating circular economy strategies with low-carbon scenarios: lithium use in electric vehicles. Environ Sci Technol 2019;53:11657–65. doi:10.1021/acs.est.9b02872.

[105] Nurdiawati A, Agrawal TK. Creating a circular EV battery value chain: end-of-life strategies and future perspective. Resour Conserv Recycl 2022;185:106484. doi:10.1016/j.resconrec.2022.106484.

[106] Shafique M, Rafiq M, Azam A, Luo X. Material flow analysis for end-of-life lithium-ion batteries from battery electric vehicles in the USA and China. Resour Conserv Recycl 2022;178:106061. doi:10.1016/j.resconrec.2021.106061.

[107] Kamran M, Raugei M, Hutchinson A. A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK: assessing the impact of shared mobility and end-of-life strategies. Resour Conserv Recycl 2021;167:105412. doi:10.1016/j.resconrec.2021.105412.

[108] Miatto A, Wolfram P, Reck BK, Graedel TE. Uncertain Future of American Lithium: a Perspective until 2050. Environ Sci Technol 2021;55:16184–94. doi:10.1021/acs.est.1c03562.

[109] Richa K, Babbitt CW, Gaustad G, Wang X. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour Conserv Recycl 2014;83:63–76. doi:10.1016/j.resconrec.2013.11.008.

[110] Ziemann S, Rat-Fischer C, Müller DB, Schebek L, Peters J, Weil M. A critical analysis of material demand and recycling options of electric vehicles in sustainable cities. Matériaux Tech 2017;105:515. doi:10.1051/mattech/2018028.

[111] Bobba S, Mathieux F, Blengini GA. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. Resour Conserv Recycl 2019;145:279–91. doi:10.1016/j.resconrec.2019.02.022.

[112] Yang H, Song X, Zhang X, Lu B, Yang D, Li B. Uncovering the in-use metal stocks and implied recycling potential in electric vehicle batteries considering cascaded use: a case study of China. Environ Sci Pollut Res 2021;28:45867–78. doi:10.1007/s11356-021-13430-7.

[113] Thorne R, Aguilar Lopez F, Figenbaum E, Fridstrøm L, Müller DB. Estimating stocks and flows of electric passenger vehicle batteries in the Norwegian fleet from 2011 to 2030. J Ind Ecol 2021;2025:1–14. doi:10.1111/jiec.13186.

[114] Suriyanon W, Jakrawatana N, Suriyanon N. Material flow of nickel in nickel metal hydride batteries waste and possible circularity improvement in Thailand. Clean Technol Environ Policy 2022;24:887–99. doi:10.1007/s10098-021-02229-2.

[115] Sun X, Hao H, Zhao F, Liu Z. The dynamic equilibrium mechanism of regional lithium flow for transportation electrification. Environ Sci Technol 2019;53:743–51. doi:10.1021/acs.est.8b04288.

[116] Knobloch F, Hanssen SV, Lam A, Pollitt H, Salas P, Chewpreecha U, et al. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat Sustain 2020;3:437–47. doi:10.1038/s41893-020-0488-7.

[117] Peshin T, Sengupta S, Azevedo IML. Should India move toward vehicle electrification? Assessing life-cycle greenhouse gas and criteria air pollutant emissions of alternative and conventional fuel vehicles in india. Environ Sci Technol 2022;56:9569–82. doi:10.1021/acs.est.1c07718.

[118] Liu Z, He Y, Zhang YJ, Qin CX. The life cycle environmental rebound effect of battery electric vehicles in China: a provincial level analysis. Appl Econ 2021;53:2888–904. doi:10.1080/00036846.2020.1870652.

[119] Banza Lubaba Nkulu C, Casas L, Haufroid V, De Putter T, Saenen ND, Kayembe-Kitenge T, et al. Sustainability of artisanal mining of cobalt in DR Congo. Nat Sustain 2018;1:495–504. doi:10.1038/s41893-018-0139-4.

[120] Sughis M, Nawrot TS, Haufroid V, Nemery B. Adverse health effects of child labor: high exposure to chromium and oxidative dna damage in children manufacturing surgical instruments. Environ Health Perspect 2012;120:1469–74. doi:10.1289/ehp.1104678.

[121] Cavalett O, Cherubini F. Unraveling the role of biofuels in road transport under rapid electrification. Biofuels, Bioprod Biorefining 2022:1–16. doi:10.1002/bbb.2395.

[122] Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, et al. Recycling lithium-ion batteries from electric vehicles. NatureNature 2019;575:75–86. doi:10.1038/s41586-019-1682-5.
[123] Ciez RE, Whitacre JF. Examining different recycling processes for lithium-ion batteries. Nat Sustain 2019;2:148–56. doi:10.1038/s41893-019-0222-5.
[124] Neubauer J., Smith K., Wood E., Pesaran A. Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries. 2015.
[125] Tao Y, Rahn CD, Archer LA, You F. Second life and recycling: energy and environmental sustainability perspectives for high-performance lithium-ion batteries. Sci Adv 2021;7:1–17. doi:10.1126/sciadv.abi7633.
[126] Guo M, Mu Y, Jia H, Deng Y, Xu X, Yu X. Electric/thermal hybrid energy storage planning for park-level integrated energy systems with second-life battery utilization. Adv Appl Energy 2021;4:100064. doi:10.1016/j.adapen.2021.100064.
[127] Engel H., Hertzke P., Siccardo G. Second-life EV batteries: the newest value pool in energy storage. 2019.
[128] Electropaedia. Traction Batteries for EV and HEV Applications 2022. https://www.mpoweruk.com/traction.htm#:~:text=Typical capacity 0.4 - 1.2 kWh (33 Ah - 100Ah.) (accessed October 22, 2022).
[129] Xiao B, Ruan J, Yang W, Walker PD, Zhang N. A review of pivotal energy management strategies for extended range electric vehicles. Renew Sustain Energy Rev 2021;149:111194. doi:10.1016/j.rser.2021.111194.
[130] Jay Ramey. Stellantis' First Hydrogen Vans Enter Production 2021.
[131] Unterlohner F. Comparison of hydrogen and battery electric trucks. 2020.
[132] Pederzoli DW, Carnevali C, Genova R, Mazzucchelli M, Del Borghi A, Gallo M, et al. Life cycle assessment of hydrogen-powered city buses in the High V.LO-City project: integrating vehicle operation and refuelling infrastructure. SN Appl Sci 2022;4:57. doi:10.1007/s42452-021-04933-6.
[133] Köhler U, Antonius C, Bäuerlein P. Advances in alkaline batteries. J Power Sources 2004;127:45–52. doi:10.1016/j.jpowsour.2003.09.006.
[134] Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: an updated review. Energy Sustain Dev 2010;14:302–14. doi:10.1016/j.esd.2010.09.007.
[135] Buchmann I. Batteries in a Portable World - A Handbook on Rechargeable Batteries for Non-Engineers. Fourth 2017.
[136] Sudworth J. The sodium/nickel chloride (ZEBRA) battery. J Power Sources 2001;100:149–63. doi:10.1016/S0378-7753(01)00891-6.
[137] Dustmann CH. Advances in ZEBRA batteries. J Power Sources 2004;127:85–92. doi:10.1016/j.jpowsour.2003.09.039.
[138] Kim MS, Ryu JH, Deepika, Lim YR, Nah IW, Lee KR, et al. Langmuir–Blodgett artificial solid-electrolyte interphases for practical lithium metal batteries. Nat Energy 2018;3:889–98. doi:10.1038/s41560-018-0237-6.
[139] Zhang K, Liu W, Gao Y, Wang X, Chen Z, Ning R, et al. A high-performance lithium metal battery with ion-selective nanofluidic transport in a conjugated microporous polymer protective layer. Adv Mater 2021;33:1–9. doi:10.1002/adma.202006323.
[140] Wei S, Xu S, Agrawral A, Choudhury S, Lu Y, Tu Z, et al. A stable room-temperature sodium-sulfur battery. Nat Commun 2016;7. doi:10.1038/ncomms11722.
[141] Chen H, Xu Y, Liu C, He F, Hu S. Storing Energy in China—an overview. Storing Energy 2016:509–27 Elsevier. doi:10.1016/B978-0-12-803440-8.00024-5.
[142] Manthiram A, Yu X. Ambient temperature sodium-sulfur batteries. Small 2015;11:2108–14. doi:10.1002/smll.201403257.
[143] Liu D, He B, Zhong Y, Chen J, Yuan L, Li Z, et al. A durable ZnS cathode for aqueous Zn-S batteries. Nano Energy 2022;101:107474. doi:10.1016/j.nanoen.2022.107474.
[144] Li W, Wang K, Jiang K. A Low Cost Aqueous Zn–S Battery Realizing Ultrahigh Energy Density. Adv Sci 2020;7:1–8. doi:10.1002/advs.202000761.
[145] Luo LW, Zhang C, Wu X, Han C, Xu Y, Ji X, et al. A Zn-S aqueous primary battery with high energy and flat discharge plateau. Chem Commun 2021;57:9918–21. doi:10.1039/d1cc04337d.
[146] Xu X, Hui KS, Dinh DA, Hui KN, Wang H. Recent advances in hybrid sodium–air batteries. Mater Horizons 2019;6:1306–35. doi:10.1039/C8MH01375F.
[147] Pan J, Xu YY, Yang H, Dong Z, Liu H, Xia BY. Advanced architectures and relatives of air electrodes in Zn–air batteries. Adv Sci 2018;5. doi:10.1002/advs.201700691.
[148] Kordesch K, Gsellmann J, Peri M, Tomantschger K, Chemelli R. The rechargeability of manganese dioxide in alkaline electrolyte. Electrochim Acta 1981;26:1495–504. doi:10.1016/0013-4686(81)90021-9.
[149] Zebra. When is it time to replace your printer battery? Before it's too late. 2016.
[150] Gupta N, Kaur N, Jain SK, Singh Joshal K. Smart grid power system. Adv. Smart Grid Power Syst. 2021:47–71 Elsevier. doi:10.1016/B978-0-12-824337-4.00003-5.
[151] Gruber PW, Medina PA, Keoleian GA, Kesler SE, Everson MP, Wallington TJ. Global Lithium Availability. J Ind Ecol 2011;15:760–75. doi:10.1111/j.1530-9290.2011.00359.x.
[152] Miedema JH, Moll HC. Lithium availability in the EU27 for battery-driven vehicles: the impact of recycling and substitution on the confrontation between supply and demand until 2050. Resour Policy 2013;38:204–11. doi:10.1016/j.resourpol.2013.01.001.
[153] Simon B, Ziemann S, Weil M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: focus on Europe. Resour Conserv Recycl 2015;104:300–10. doi:10.1016/j.resconrec.2015.07.011.
[154] Palencia JCG, Araki M, Shiga S. Energy, environmental and economic impact of mini-sized and zero-emission vehicle diffusion on a light-duty vehicle fleet. Appl Energy 2016;181:96–109. doi:10.1016/j.apenergy.2016.08.045.
[155] Yano J, Muroi T, Sakai S ichi. Rare earth element recovery potentials from end-of-life hybrid electric vehicle components in 2010–2030. J Mater Cycles Waste Manag 2016;18:655–64. doi:10.1007/s10163-015-0360-4.
[156] Reuter B. Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles. Int J Interact Des Manuf 2016;10:217–27. doi:10.1007/s12008-016-0329-0.
[157] Pehlken A, Albach S, Vogt T. Is there a resource constraint related to lithium ion batteries in cars? Int J Life Cycle Assess 2017;22:40–53. doi:10.1007/s11367-015-0925-4.
[158] Deetman S, Pauliuk S, Van Vuuren DP, Van Der Voet E, Tukker A. Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ Sci Technol 2018;52:4950–9. doi:10.1021/acs.est.7b05549.
[159] Fishman T, Myers RJ, Rios O, Graedel TE. Implications of emerging vehicle technologies on rare earth supply and demand in the United States. Resources 2018;7:1–15. doi:10.3390/resources7010009.
[160] Calisaya-Azpilcueta D, Herrera-Leon S, Lucay FA, Cisternas LA. Assessment of the supply chain under uncertainty: the case of Lithium. Minerals 2020;10:1–20. doi:10.3390/min10070604.
[161] Bobba S, Bianco I, Eynard U, Carrara S, Mathieux F, Blengini GA. Bridging tools to better understand environmental performances and raw materials supply of traction batteries in the Future EU Fleet. Energies 2020;13:2513. doi:10.3390/en13102513.