Renewable and Sustainable Energy Reviews 191 (2024) 114176

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

# Sustainability challenges throughout the electric vehicle battery value chain

Anahita Jannesar Niri [a,*], Gregory A. Poelzer [b], Steven E. Zhang [c], Jan Rosenkranz [a], Maria Pettersson [b], Yousef Ghorbani [d,**]

[a] Department of Civil, Environmental, and Natural Resource Engineering, Luleå University of Technology, SE 97187, Luleå, Sweden
[b] Department of Social Sciences, Technology and Arts, Luleå University of Technology, SE-97187, Luleå, Sweden
[c] Independent Researcher, 39 Kiewiet Street, Helikon Park, Randfontein, 1759, South Africa
[d] School of Chemistry, University of Lincoln, Joseph Banks Laboratories, Green Lane, Lincoln, Lincolnshire, LN6 7DL, United Kingdom

ARTICLE INFO

*Keywords:*
Climate change
Automotive industry
Battery minerals
Sustainable supply of minerals
Energy supply

ABSTRACT

The global commitment to decarbonizing the transport sector has resulted in an unabated growth in the markets for electric vehicles and their batteries. Consequently, the demand for battery raw materials is continuously growing. As an illustration, to meet the net-zero emissions targets, the electric vehicle market demand for lithium, cobalt, nickel, and graphite will increase 26-times, 6-times, 12-times, and 9-times respectively between 2021 and 2050. There are diverse challenges in meeting this demand, requiring the world to embrace technological and knowledge advancements and new investments without provoking conflicts between competing goals. The uncertainties in a sustainable supply of battery minerals, environmental, social and governance complexities, and geopolitical tensions throughout the whole battery value chain have shaped the global and regional concerns over the success of transport decarbonization. Here, focusing on the entire value chain of electric vehicle batteries, the approaches adopted by regulatory agencies, governments, mining companies, vehicle and battery manufacturers, and all the other stakeholders are evaluated. Bringing together all these aspects, this literature review broadens the scope for providing multifaceted solutions necessary to optimize the goal of transport decarbonization while upholding sustainability criteria. Consolidating the previously fragmented information, a solid foundation for more in-depth research on existing difficulties encountered by governmental and industrial actors is created. The outcomes of this study may serve as a baseline to develop a framework for a climate smart and resource efficient supply of batteries considering the unique impacts of individual players.

## 1. Introduction

Fossil fuels continue to be the main source of energy production, and the automotive industry is the main end-user of fossil fuel-derived commodities. The industry significantly contributes to economic productivity but also to global greenhouse gas (GHG) emissions, air pollution, and consequently global warming in which the growing world population also plays an important role [1,2]. Between 1990 and 2019 the global population increased by 46%- from above $5.3 \times 10^9$ to almost $7.8 \times 10^9$ [3]. During this period, the amount of global $CO_2$ emission from the transport sector increased from 4.61 Gt to 8.22 Gt which accounted for 17 % of the global GHG emissions [4]. Considering the role of this sector in climate change, the achievement of the global goal of climate neutrality by 2050 necessitates decreasing the transport

*Abbreviations:* EV, Electric vehicle; BEV, Battery Electric Vehicle; GHG, Greenhouse Gas; IEA, International Energy Agency; ESG, Environmental, Social, and Governance; LIB, Lithium-Ion Battery; REE, Rare Earth Element; ICEV, Internal Combustion Engine Vehicle; SDG, Sustainable Development Goal; HEV, Hybrid electric vehicle; SLO, Social License to Operate; HVAC, Heating, Ventilation, and Air Conditioning system; V2G, Vehicle-to-Grid system; DRC, Democratic Republic of Congo; EOL, End-of-Life; LCSA, Life Cycle Sustainability Assessment; COP21, 21st Conference of Parties; MSP, Mineral Security Partnership; GRI, Global Reporting Initiative; SEC, Securities and Exchange Commission; CBAM, Carbon Border Adjustment Mechanism; IRA, Inflation Reduction Act; TSM, Towards Sustainable Mining; IRMA, Initiative for Responsible Mining Assurance.

* Corresponding author.
** Corresponding author.
*E-mail addresses:* anahita.jannesar.niri@ltu.se (A. Jannesar Niri), yghorbani@lincoln.ac.uk (Y. Ghorbani).

https://doi.org/10.1016/j.rser.2023.114176
Received 20 January 2023; Received in revised form 1 December 2023; Accepted 7 December 2023
Available online 16 December 2023
1364-0321/

sector's dependency on fossil fuels [5].

Phasing out fossil-fueled vehicles and replacing them with battery electric vehicles (BEVs) has been considered a mitigative solution to climate change and governments in many countries have adopted this green transport revolution. BEV adoption, which relies on batteries for electrical energy storage, has resulted in growing demands for rechargeable batteries, especially lithium-ion batteries (LIBs) with their high energy and power density, and long lifespan-useful life around ten years [6]. Consequently, suppliers around the world are striving to keep up with the rapid pace of demand growth in battery raw materials. Various factors have disrupted the supply chains of battery materials creating a serious mix of risks for secure and rapid road transport decarbonization. To reiterate, these factors encompass geographical distribution of the different stages of battery minerals supply chains (e.g., almost 86 % of the mined lithium ores come from Australia, Chile, and China), unpredictable incidents (e.g., COVID-19 pandemic highlighting the vulnerability of a global supply and demand system) [7,8], geopolitical issues (e.g., increasing prices of aluminum due to Russia's invasion of Ukraine), and environmental, social, and governance (ESG) complexities (e.g., water shortages and local communities' protests in Chile) [9,10]. Thus, a sustainable supply of materials has paramount importance to progress towards an efficient transition to a low carbon future.

To address the pertinent pressure of monopolization and insecure supply of battery metals and minerals, the governments of the most countries have initiated a variety of policies and implemented landmark measures based on their positions in the battery value chain. Examples of these policies include developing domestic production, diversifying suppliers at different stages of value chain, improving security mechanisms, increasing refining and recycling capacity, technological innovations, substituting battery components, developing responsible sourcing, minimizing environmental and social risks, and strengthening governance systems [11,12].

The source of electricity consumed in the whole lifecycle of batteries can determine whether electric vehicles (EVs) would be a satisfactory solution to climate change since extracting and processing battery raw materials, battery manufacturing and recycling, and battery charging require high amount of energy [13]. Several countries such as Poland, the Czech Republic, Bulgaria, Turkey, and Estonia are highly dependent on fossil fuels to generate electrical power [14]. Many areas still lack industry-wide progress in terms of GHG emissions that can deteriorate global climate change. Regarding these facts, renewable energy integration into all sectors involved in producing EVs is inevitable. Additionally, knowledge advancements and technological innovations in battery related processes are deemed to be very desirable to decrease GHG emissions, cost, and energy consumption [15–17]. Finally, the grid impacts from the penetration of EVs into the market should not be overlooked, which is one of the important challenges to EV adoption globally. Certain actions, particularly in developing countries, are still needed to improve the performance, efficiency, and capacity of the electrical grid [18].

Although EV markets are witnessing exponential growth, there are still impediments to decarbonizing the transport sector globally. The world is encountering multifaceted challenges resulting from the various actors involved in the EV value chain, which shows the need for further consideration and research. There are a variety of studies on different aspects of this transition. Focusing on the value chain of the EV battery, the intended objective of this comprehensive literature review is to bring together previously fragmented diverse and global perspectives to evaluate the existing gaps from the standpoints of knowledge, innovation, legislation, and reliability in a categorized structure. To accomplish this, in this study, governments, policymakers, decision-makers, mining industry, battery manufacturers and recyclers, car companies, power industry, customers, and affected communities are included in the list of the considered players in road transport electrification. The repercussions in the current implemented strategies are thoroughly explored to clarify the actions and policies that may not entirely align with the sustainable development goals (SDGs). The outcomes of this study can be utilized in future studies on establishing a systematic and sustainable direction towards a climate-smart and resource efficient framework for sustainable production of EV batteries.

This study is organized as follows. Section 2. reviews the actions that the automotive industry has taken and conceivably could still take to mitigate climate change while clarifying the regulatory restrictions. In Section 3, the challenges and difficulties that need to be addressed to attain the goal of road transport electrification are comprehensively defined. In Section 4 the risks and opportunities in the current trend are evaluated to put forward practical solutions. Finally, in Section 5 a summary and outlook are provided.

## 2. The automotive industry in the epoch of green transition

Due to the growing concern about global warming and environmental pollution, in the 21st Conference of Parties (COP21), held in Paris in 2015, under the Paris Agreement, 196 countries committed to take actions to reduce their emissions through adopting national plans, legislation, and policies such as abolishing subsidies on fossil fuels and implementing carbon pricing [19]. As a result of this global treaty, sustainability approaches have become a strategic priority for the automotive industry [20]. Sustainable practices employed in the industry cover the entire range of its activities [20,21].

- Research and development, and engineering (e.g., product sustainability);
- Supply chains (i.e., providing a sustainable supply chain considering local, social, cultural, ecological, and economic aspects);
- Manufacturing and operations (i.e., sustainable production, reverse logistics);
- Mobility services and vehicle usage (i.e., emission reduction);
- Supporting and developing a circular economy;
- Fair labor policy for the automotive value chain; and
- Sustainability in information technology (e.g., energy consumption in data centers).

Vehicle electrification is the approach taken by the industry to play its part in the global move towards a sustainable and green economy [22]. Many countries are trying to decrease or ban the production of conventional vehicles and promote EV manufacturing and adoption [23]. The UK, France, Germany, Netherlands, and other countries have pursued the Paris Agreement goals and followed developing strategies to stop producing internal combustion engine vehicles (ICEVs) by 2040 [24]. Norway plans to stop the sale of petrol engine vehicles by 2025, and South Africa is trying to increase its EV market share to 20 % by 2030 [25]. The governments are also implementing supportive policies to encourage consumers to opt for EVs such as purchase and electricity subsidies in Japan, Germany, Finland, France, and Austria [26,27]. Hybrid electric vehicles (HEVs) are also considered an instant and promising step towards transport decarbonization because of their potential for emission abatement. Many consumers opt for HEVs because of their merits of wider driving range and their fuel diversity and accessibility in comparison with current BEVs [28]. Table 1 summarizes the penetration levels of EVs, including BEVs and plug-in HEVs, in specific regions in 2022.

**Table 1**
Regional statistics for the deployment of EVs in 2022 [29].

| | Region | | |
|---|---|---|---|
| | China | EU | U.S. |
| **EV Registration number (million)** | 5.9 | 2.7 | 1 |
| **EV sales share (%)** | 30 | 24 | 8 |

The path to achieving the goal of sustainability in the automotive industry can be clouded by the lack of sound governance [21]. As an illustration, Kaviani et al. [30] analyzed the factors obstructing the successful implementation of reverse logistic in the Iranian automotive industry. Reverse logistics has gained significant importance to this sector due to strict environmental policies and finite primary resources. Based on the results of this study, the complexities to find third parties interested in providing reverse logistics and the lack of qualified performance management mechanism are the hinderances to apply this approach. Moreover, the conflicts over sustainability activities considering the environmental, social, and economic performance of car manufacturers require a governance body to manage and scrutinize all the sustainability measures during a vehicle's closed-loop lifecycle [31, 32]. The environmental and social effects of a product during its life cycle could not be overseen without governance policies [32]. The automakers should comply with reasonable environmental (e.g., carbon neutral manufacturing), social (e.g., human rights), and governance (e.g., corporation strategies, code of ethics, risk management) policies [33–35].

The ESG criteria are utilized as a framework to assess a company's sustainability approach [36,37]. Companies should release reports including information about ESG factors at regular intervals [36]. These reports form a holistic perception of a company's financial future and show whether a firm's sustainability initiatives are helping it to reach the UN SDGs [38]. Concerning ESG data disclosure, there is a persistent problem called greenwashing, which means there are contradictions between what firms report and what they really perform. Detailed research on this subject has been conducted. For instance, Chen et al. [39], Glavas et al. [40], Pei-Yi Yu et al. [41], and Liu et al. [42] evaluated the current regulations to find how to prevent these misleading behaviors, and to propose effective mechanisms to spot and discourage greenwashing. However, the development of evaluation instruments and assessment methodology transparency to scrutinize the reliability of the sustainability declarations and enhance transparency is of paramount importance.

Automotive industries are striving to strengthen their positions in the value-added operations and production of EV components to ameliorate geopolitical disparities endangering their productivity and competitiveness [43,44]. This fact has forced the automotive industry to deal with battery manufacturers [45], and also to secure the mid- and long-term sustainable supply of battery raw materials through investing in battery minerals mining and refining projects [46]. Examples are Build Your Dream (BYD), Tesla, and Volkswagen which are the main EV market players investing mostly in nickel and lithium [10].There are other factors that affect countries' automotive sectors' transitions to EVs including consumer purchase intention [47], systemic disruptions in supply chains of the industry such as semiconductor shortage [48], limited capacity of electrical grids [15], carbon-intensive electricity mix [49], lack of associated technologies such as charging infrastructure [43], and even, lack of advanced knowledge, supportive and implementable rules, and authoritarian frameworks in some countries [50].

In addition to vehicle electrification other opportunities exist in minimizing GHG emissions from transport sector before the widespread commercialization of EVs. A stream of research has been done on different technologies. Ternel et al. [51], asserted that advanced bio-natural gas vehicles can efficiently decrease tailpipe emissions - a 15 % reduction in comparison with standard bio-natural gas vehicles. Hasan et al. [52] assessed the effect of using methanol and diesel combination on the traits of emissions and combustion efficiency of a 4-cylinder compression ignition engine in different conditions. Based on the result, in all conditions the $CO_2$ emissions for methanol/diesel blended engines (almost 1.9 ppm) were lower than that for diesel engines (about 3.4 ppm). Yu et al. [53] worked on how to optimize the energy efficiency of heavy-duty vehicles. The study proposed a design of a compound coupled hydro-mechanical transmission prototype, enabling energy reuse and recovery in heavy duty vehicles. Using carbon fibers in different parts of vehicles to reduce the weight and increase the fuel efficiency of vehicles is another measure. The ongoing engineering task regarding this measure is to increase the energy efficiency of carbon fiber manufacturing process to address its high energy demand (1150.5–960 MJ/carbon fiber Kg on average) [54,55].

There are also top-down policies that can be implemented or have been pursued in different countries to decrease GHG emissions such as vehicle age regulations [56], traffic congestion management, distance-based taxes, and fuel quality. Since different countries have different capabilities, global sustainable development status, and technological improvements [57], in addition to top-down policies, market-based efforts to decrease GHG emissions from the automotive sector are crucial [58,59].

## 3. Challenges facing the car electrification

Electrical road transport has disruptively changed the automotive industry value chain. In this new value chain, there are new key players that provide batteries and their components, electric power systems, and recycling and reuse services which determine whether the produced EVs have low environmental impact, follow emissions legislation, and respect human dignity and rights. Car manufacturers are striving to ensure the green supplies of these products and services. To flourish in the era of sustainability, it is crucial for carmakers to interact with ethical suppliers employing environmentally sustainable and ethically justifiable approaches [60]. However, automotive industries all over the world are facing various challenges in the pursuit of those required actions. In this section, these challenges will be clarified and examined in detail in three individual subsections in order to identify the gaps and opportunities in the taken approaches.

### *3.1. Land use conflicts*

With the growing demand for EVs, the requests for LIBs are climbing simultaneously. Many governments and companies are determined to assure the sustainability of their LIB supply chains by locally developing different production stages [61]. Toyota Motor Corporation is a good example that has projected to construct a battery factory in North Carolina on a land with renewable energy availability for its future production of EVs. This plant will commence production of battery packs in 2025 aiming to develop and localize its automotive battery production [62]. Minimizing the cost and environmental impacts resulting from transportation and logistics systems associated with the end-of-life (EOL) LIBs is another reason why many countries such as the UK venture upon forming a closed-loop system in their battery supply chains. This can be achieved by localizing or co-locating LIB recycling factories which provide car manufacturers of each country with a domestic secondary resource of battery materials, and simultaneously enable them to deal with the waste materials [63].

Localizing these manufacturing and recycling factories has been hampered by the difficulties in accessing sizeable land areas [64]. Obtaining multiple land use permits, including but not limited to local land use approval, air and water permit, local health and safety permit, and permits from local enforcement agencies, is obligatory for companies who want to build new or expand their facilities [65]. This issue has put a limit on the quantity of the lands that can be utilized for such industrial activities and causes conflicts over the use and access to lands [66]. To cope with this challenge, governments typically play the coordinating role and can take actions such as.

- Collaborating with industry to prioritize sites with the least possibility of political disagreement and social conflicts [31];
- Providing capital for technological advancements to prevent or minimize environmental problems associated with their activities [31];

- Devising plans to dislocate and reinstate the communities losing lands due to such industrial activities [67]; and
- Adopting well-designed national land-use planning while laying stress on its social impact assessments [68].

Moreover, the rising request for mineral resources has resulted in the expansion of mining activities to extract the necessary amounts of raw materials and minerals employed in technologies associated with this transition. These activities have caused conflicts between mining actors and community groups. The lands exploited for raw material extraction can make it impossible for other small and large businesses and industries to develop during mining operations or even after mine rehabilitation, for example, fisheries, forestry, and farming [69]. Competition over land use between indigenous communities and mining companies is a common point of conflict. For instance, in Finland, the tourism industry, reindeer herding, and environmental and nature protection are usually the mining companies' rivals for land acquisition [70]. In Sweden, the process of getting permission to start or develop mining operations can be hampered by Sami people working as reindeer herders. The mining industry often comes into conflict with the reindeer husbandry, which constitutes an important factor in the land use rights and culture of Sami communities. To address such conflicts, a dynamic involvement of both a flexible and inclusive approach and a restrictive approach in the governance system is needed. As a result, multiple pathways to sustainability can be considered and finally a well-timed, credible, and foreseeable decision can be made [71].

Affected communities demand more engagement in the decision making and want to benefit from mining operations [72]. They will more likely accept the establishment of a new mine if they are adequately engaged as stakeholders and responsible companies act based on sustainable development regulations. This community acceptance of establishing or developing mining operations often known as social license to operate (SLO) should be gained and maintained by involved companies within the context of trust-based relationships [73,74]. Acquiring a SLO which demonstrates the mining companies' effective management of social and environmental risks has been gaining growing importance in mineral resource development [75] and the lack of SLO can disrupt the supply of raw materials. Therefore, to develop a mine, legitimate measures should be implemented by the industry and governments to deal with the local community's concerns and cement the stakeholder relationships in mining communities [73]. It is important that all members of the project agree on a single ethical framework while respecting cultural norms. This should be done well in advance of initiating transparent technical planning. The improvement of the governance capacity providing the community with well-developed economic, legal, and social establishments is also perceived as an influential measure to facilitate the process of gaining and maintaining a SLO [76].

The renewable energy sector, playing an important role in minimizing GHG emissions in the whole value chain of EVs, needs large land areas for wind parks, solar farms, and water reservoirs for hydropower stations. However, the limitation of available lands has also faced this sector. Other sustainability aspects such as food security and biodiversity conservation have conflicts over lands with this sector [77]. Further improvements in the current policies and technological advancements are needed due to the significant environmental impacts (e.g., water and soil acidification and ozone depletion) associated with renewable energies deployment [78].

However, what should not be overlooked is the fact that global transport decarbonization aligned with SDGs requires all the countries to consider environmental and social indicators, while making efforts to ensure the sustainability of their EV markets. Although in developed countries such as Europe and United States environmental and social sustainability are becoming important as much as their economic growth targets [79], there are many countries, especially developing countries and emerging economies such as China, where the governments transfer the lands to polluting industries to improve their economic climates without considering the environmental and social consequences of their approaches [80]. Due to the goal-conflicts in the green transition, there is a growing need for transparency and accountability in the sustainability approaches. Openness in decision making processes, which shed light on the stakeholders 'real interests, encourages them to make more informed decisions.

### 3.2. Intensive energy requirement

#### 3.2.1. Battery manufacturing

Although transport decarbonization is seen as the prerequisite to climate change mitigation [81], the LIB manufacturing processes make a significant net contribution to lifecycle GHG emissions from BEVs. Battery production consists of energy intensive processes, including cell production, formation/aging, and cell assembly [82,83]. There are strictly interlinked processes in battery production, a large number of which are non-value adding activities. Consequently, considerable amounts of the embodied energy and associated costs go toward non-value adding stages. This issue can reduce product competitiveness in terms of price and increase its environmental footprints [84,85]. Based on the Romare et al. [86] report assessing the studies on GHGs emitted and energy used during specific kinds of LIBs production, approximately 97–181 kWh energy is used to produce one kWh storage capacity. This brings about significant GHG emissions. Kim et al. [87] used the data from the Ford Focus BEV and the company's battery industry to evaluate the cradle-to-gate GHG emissions for the LIB with 24 kWh capacity. The results showed that the amount of emitted GHGs was equal to 3.4 metric tons of $CO_2$-eq (140 kg $CO_2$-eq per kWh or 11 kg $CO_2$-eq per kg of battery), and among all the processes of battery production, cell manufacturing amounted to 45 % of the GHG emissions. Based on that study, the primary energy demand for the Ford Focus BEV battery cell and pack manufacturing was 120 MJ for each kg of battery.

According to the International Energy Agency (IEA) report [88], about 4670 GWh is the announced capacity expansion of battery production by 2030. Considering the driving range limitation which is between 200 and 350 Km with a fully charged battery (a battery's energy storage capacity can differ approximately from 10 to 200 kWh), it can be concluded that there will be a huge demand for energy production in the coming future to meet the objective of road transport decarbonization [43]. Technological solutions along with production planning are necessary approaches toward the reduction of energy demand. Various studies have been conducted on evaluating the possible solutions to reduce the energy demand for battery production. Al-Shroofy et al. [89] assessed a solvent-free dry powder coating method and compared it with the conventional wet slurry-based method. The outcomes of the research showed that the former is less energy demanding and more environmentally friendly. Moreover, Vogt et al. [90], investigated the influences of the size and planning procedures of heating, ventilation, and air conditioning (HVAC) systems which are the main components of the dry rooms for battery cell assembly. In light of the results gained from the case study, a 7.4 % decrease in the amount of energy used during a year can occur through changing the design of HVAC system components.

The source of electricity used in the manufacturing plants plays a crucial role in the amount of GHG emissions. Carbon-intensive electricity mix considerably increases the level of GHG emissions throughout battery manufacturing. This makes the location of these factories, in terms of their access to renewable energy, an important contributing factor to the reduction of EV's lifecycle emissions. One considered solution to this issue is to enact legislation to incentivize manufacturers and investors to prioritize green energy sources while choosing a production location or power generation mix [85]. Moreover, to motivate battery manufacturers to put determined efforts on reducing carbon emissions during battery production process, some countries are taking severe policy steps such as U.S. inflation reduction act (IRA) and EU's carbon border adjustment mechanism (CBAM) [91,92].

The EU's CBAM is the law enforcing higher costs for the import of high-carbon products into the European Union. The U.S. IRA provides billions of dollars to domestically produce clean vehicles and their components including batteries. This approach will be backed by the money given to the US Department of Energy to finance the manufacturers to reequip their assembly lines to manufacture clean products [93]. To examine these almost new policies to see whether they have negative consequences, further in-depth research is needed. For instance, regarding the research done by Mirza et al., US IRA could give rise to trade-offs between energy security and environmental concerns which necessitates setting the multi-dimensional regulations [94].

Besides, another initiative is the introduction of a battery passport into the market. The battery passport provides digital data on the battery's mineral components' origins, ESG metrics, life-cycle carbon emissions, performance, reuse, and recycling. It is perceived that the provided traceability by a battery passport forces manufacturers to produce sustainable and responsible batteries. However, there are a variety of prerequisites to achieve this common ambition (e.g., Commensurate systems for data collecting, processing, and sharing and skilled workforce for data documentation) [95].

#### 3.2.2. Infrastructure requirements

The infrastructure that supplies electricity to charge EVs has different components including distribution transformers, energy meters, cables, and distribution panels. There are generally six different types of charging stations in terms of the technology used to charge the batteries known as slow charging, fast charging, ultra-fast charging, battery swapping, wireless charging, and mobile charging stations [96–98]. Today, the number of charging stations on the roads is insufficient to sustain growing EV adoption [99]. For example, in European countries including Turkey, there were around 535,731 charging stations in 2022 [100], which even based on the most prudent scenario, needs to increase to at least 3.4 million public charging stations by 2030 [101].

The tremendous request for charging EVs considerably affects grid characteristics such as electrical, voltage, and current, resulting in the shortage of electricity and power fluctuations. Additionally, owing to the rising number of fast charging facilities, which is going to gain more importance, especially in the future when the number of EVs will climb, certain issues such as the increasing time of high demand, voltage instability, and reliability should be solved to provide satisfactory grid performance [99]. To roll out charging facilities, the current state of grid infrastructures should be considered to develop the interaction between EVs and the grid and to provide corresponding charging systems. Otherwise, EVs can result in grid stress, increasing congestion, power consumption, and power losses [102].

Various studies analyzed the merits and immerits of adopting different technologies. For example, implementing suitable charging strategies such as centralized and decentralized charging methods without a network expansion from the national power transmission system [103,104]. Bibak and Mogulkoç [105] evaluated the vehicle-to-grid (V2G) systems and their combination with other solutions including renewable energy and smart grid to clarify their potential for solving the current pressure on energy power systems. Wan et al. [106] worked on how to preserve the privacy of EV owners using V2G systems. Su et al. [107] investigated the influence of EVs on the power industry and, also intelligent energy systems to minimize energy consumption. Yap et al. [108] asserted that developing energy management measures is crucial to improve charging and discharging operations. Mehrjerdi [109] conducted research on generation capacity expansion via energy storage systems instead of increasing the capacity of the network, and the challenges of dealing with increasing energy load on power networks. However, energy storage systems currently exacerbate all issues associated with batteries.

Implementing all the mentioned solutions has consequences influencing the power systems, the environment, the total cost, and individual mobility choices. In addition, the results of using these techniques vary from region to region depending on their technological capability, energy mixes, economic climates. No unique solution exists for infrastructure issues meaning that transport decarbonization challenges needs further research in all knowledge domains.

### 3.3. Supply sustainability of battery minerals

In 2021, the global number of EVs on the roads was approximately 16.5 million, which increased to above 26 million until the end of 2022 [29,110]. To meet the net-zero emissions targets, the sales share of EVs has to increase by almost 6 % each year. it is estimated that the achievement of net-zero emissions by 2050 requires 300 million EVs in 2030 [111]. Regarding its material inputs, a typical EV needs substantially more minerals in comparison with an ICEV, especially due to its battery pack. Fig. 1 shows the battery components, coupled with the contents and mass percentages of the key minerals. Table 2 indicates the total weight of the certain key metals used to manufacture a typical ICEV and three different BEVs. The data in Fig. 1 and Table 2 and the growing EV market support the immensity of the demand for minerals.

In addition to EVs, other material intensive technologies (e.g., electricity networks, wind turbines, and solar panels) are prerequisites for addressing global warming. The growing demand for all these technologies puts pressure on the supply side of the associated raw materials. In the IEA [88] report, it is stated that by 2030, almost 31 million tons of raw materials used in green energy technologies will be needed to reach the goal of limiting global warming to 1.5° by 2050, while EVs and storage technologies account for almost 12 million tons of this huge demand. Fig. 2 illustrates the contributions of specific green technologies to the increasing mineral demands by 2030, based on three different IEA scenarios (i.e., Net-Zero Emissions (NZE) scenario, Announced Pledge Scenario (APS), and Stated Policies Scenario (STEPS)).

Moreover, Fig. 3 shows the projected increase in demand for each specific mineral necessary for green technologies by 2030 and 2050, considering different IEA scenarios [88]. The escalating demands for green technologies' raw materials are likely to hamper the deployment of EVs and other clean energy technologies. Valero et al. [114] assessed the supply risks of energy transition metals considering the green technologies global adoption for the 2016–2050 time period. The results show that minerals including but not limited to cobalt, copper, lithium, manganese, nickel, and tin are at high supply risks since their cumulative demands exceed the current available global reserves and future production potential.

Promoting new resource exploration activities, tackling battery minerals supply disruptions, expanding the recycling rates of materials, and looking for substitutions for minerals facing supply risks are preconditions for meeting this global trend. However, a wide spectrum of risks has faced the supply sustainability of battery minerals attributed to a myriad of factors. In the following subsections, these factors, along with taken approaches to address them, are evaluated, coupled with recommendations for the engaged industries.

#### 3.3.1. Geological restrictions and new mine development

The long length of time (20–25 years) between the discovery process of a mineral deposit and the start of the first mining production is a well-known challenge to the supply of battery minerals since the time remaining to meet net-zero emissions is not substantial. Even if there is a mineral resource discovered, among every 1000 primary resources only one or two of them can host a mine, and among started mining operations some of them can be prematurely closed [115]. Most of the deposits that were easy to be mined and had high ore grades have been extracted. Replacing depleted mineral deposits with new ones is getting harder and more complicated due to the lower ore grades and their more complex mineralogy. Mining these deposits could have negative influences on the transition to the green economy since they have larger environmental footprints caused by more energy and water

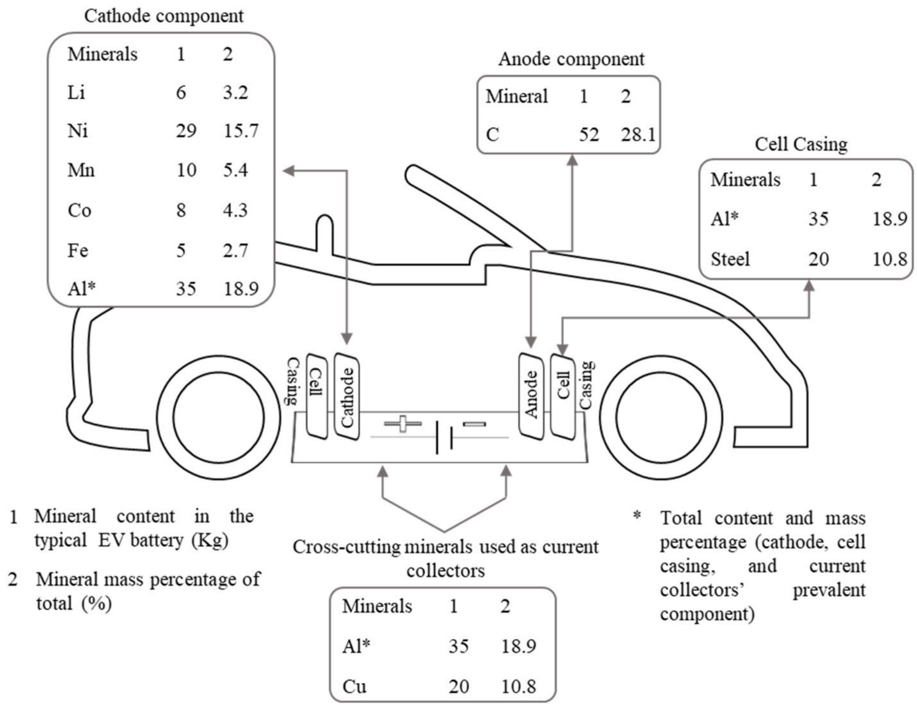


**Fig. 1.** Mineral consumption distribution in the different components of the typical EV battery produced in 2020, with an average capacity of 60 kWh. The materials used in electrolytes, binders, separators, and battery pack casing are not considered (The data is gained from Bhutada [112]).

**Table 2**
Comparison of the total weight of metals in conventional and EVs (The data is gained from Iglesias-Émbi [113]).

| Vehicle Type | ICEV[a] | BEV-NMC[b] | | |
|---|---|---|---|---|
| | | BEV-333 | BEV-622 | BEV-811 |
| **The total weight of metals** [c] **(kg)** | 179.40 | 336.22 | 330.90 | 320.93 |

[a] Li, Co, and Ni are not used for an ICEVs production.
[b] NMC shows the stoichiometric ratios between nickel, manganese, and cobalt (3:3:3/6:2:2/8:1:1) in the EV battery cathodes.
[c] the metals include Al, Cu, Pb, Zn, Cr, Mn, Ni, Co, Li, and others.

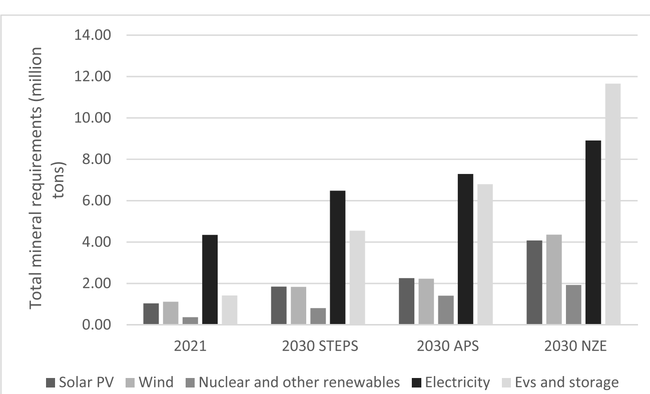


**Fig. 2.** The required minerals for specific green technologies in 2021 and the predicted requirements for 2030 based on three IEA scenarios (modified after IEA [88]).

consumption, and more waste generation. As an illustration, the analysis carried out by Valenta et al. [116] showed that the extraction of the existing known resources of undeveloped lower grade copper-ore bodies carries the intricacies of ESG issues such as Tampakan copper-gold mine,

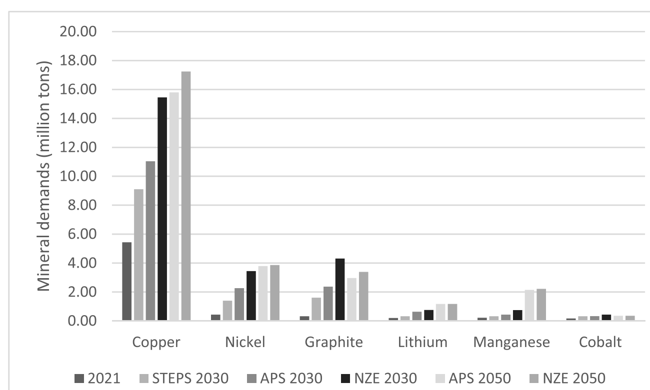


**Fig. 3.** Mineral quantities needed for green technologies (hydrogen, electricity, EVs and storage, nuclear and other renewables, wind, and solar PV) in 2021 and projected for 2030 and 2050, based on specific IEA scenarios (modified after IEA [88]).

in the Philippines facing arsenic pollution and area turmoil.

Assuming that economic concentrations of minerals will be located, the economic value of deposits is still significantly influenced by ore characteristics, which control the performance of the extraction and beneficiation processes and are determined by the deposit geology and ore mineralogy [117]. For example, the co-existence of lithium with other elements (e.g., calcium, sodium, potassium and magnesium) in its deposits leads to complexities during lithium extraction and processing, thereby affecting the economic feasibility of these processes [118]. Moreover, technological hurdles can cause valuable materials to become deposited in tailings or smelter slags due to their low recovery rates [119], such as cobalt with its complex deposit geology [120,121]. Innovative extraction techniques enabling the improvement of recovery efficiency and the extraction from both conventional and unconventional resources are required to meet the rising demand for battery minerals [118].

In 2022 and the first quarter of 2023, junior enterprises were successful in gaining financial supports -almost 1.75 billion U.S. dollars- from the governments and private companies to develop technical innovations necessary for green technologies' minerals extraction and processing, mostly in China, U.S., Canada, and Europe, especially for cobalt, rare earth elements (REEs), copper, and lithium extraction and battery and waste recycling [10]. This approach needs to be expanded globally and also cover other battery raw materials.

The responsible consumption of natural resources while minimizing the associated adverse impacts on the environment is a policy context that is dictated by the concept of sustainability to the mining sector [122,123], against a backdrop of geological reality. Thus, mining companies need to maximize their production and their profits in a sustainable manner while minimizing the overall cost. Considering these challenges related to such ore deposits, reprocessing the tailings and smelter slags is an ineluctable approach that should be extensively considered in order to successfully deal with growing depletion of primary resource [124]. To facilitate the inclusion of the battery raw materials recovered from mining and processing wastes in the market, a variety of challenges should be addressed. Studies have explored various factors including energy intensive recovery processes, the lack of comprehensive environmental and social considerations, insufficient metallurgical knowledge [125], the lack of structured and harmonized information about availability and recoverability of those resources to do feasibility studies [126], the lack of a legislative framework to back mine wastes reprocessing [127], and economic and technological constraints [128].

### 3.3.2. Environmental, social, and governance challenges

The supply of battery minerals is highly dependent on the extraction of minerals from primary resources due to the insufficient pace of technological improvements in the field of mineral and metal recycling from secondary sources. Additionally, due to the long battery lifetimes and multiple end-uses, battery recycling cannot efficiently augment short-term supply [129]. Notwithstanding the irreplaceable value of the mining industry to this green transition, it is well-known that mining operations will continue to incur environmental and social risks, particularly in the areas where governments are unable, or unwilling to protect local communities and the environment against the consequences of extraction [12,129]. Although, resource-rich countries can theoretically experience an increase in public revenue and economic growth, extracting these minerals has also resulted in social and governance complexities.

In many mining areas, the social challenges associated with mining operations such as health risks, human rights violations, life-endangering working conditions, child labor, displacement, and armed conflicts tie in with governance issues that have given rise to the persistence of corruption. Cobalt mining within the Democratic Republic of Congo (DRC), significantly by artisanal and small-scale mining operations, has been affected by such issues [130,131]. Extracting lithium deposits is accompanied by environmental impacts, particularly high-water contamination risk is the common challenge in 65 % of the lithium mines.

Vehicle electrification to address climate change aligned with respecting the rights of workers and communities and conserving the environment has led the mining industry's sustainability practices to come under immense scrutiny. Unstable and poor governance causing grave environmental and social challenges could result in mine shutdowns and create supply risks [31]. This transition should be made in a way that supports peaceful, sustainable development nationally and internationally to prevent undesirable dynamics in the complex supply and demand system. To reduce the potential of mining projects to restrict the global supply of battery minerals, the ESG complexities should be evaluated and managed throughout the whole life cycle of mining operations [132]. All aspects must be addressed independently and simultaneously, for example, governance issues should not be remediable using social or environmental mitigation measures, to create policy loopholes or greenwashing opportunities.

Mining companies should release annual sustainability reports mostly using Global Reporting Initiative (GRI) standards to provide the investors and all other involved stakeholders with transparent information concerning their dedication to ESG criteria. Some countries have tightened their current or imposed new regulations requiring the mining companies to declare their ESG performances in their sustainability report. As an example, U.S. Securities and Exchange Commission (U.S. SEC) enforces compulsory declarations of internal GHG emissions, energy supply emissions, and external emissions, if applicable, on the industry. Additionally, South Africa, Australia, Germany, China, and France have made the ESG disclosure obligatory [133]. However, a variety of studies have been conducted on the factors questioning the reliability and transparency of ESG disclosure documents. Table 3 presents some examples of these factors and their reasons, and also proposed solutions to have more harmonized and transparent sustainability reports, and more importantly, to improve industry's real actions. Although it is unclear how ESG-type accountability frameworks would be applicable to small-scale suppliers of materials, such as informal or artisanal mines.

### 3.3.3. The geopolitical aspects

The geopolitical map formed by the regions and states rich in fossil fuel resources has been changing through the global energy transformation. Oil, gas, and coal have defined energy geopolitics for more than one hundred years. The largest coal reserves are found in the

**Table 3**
Solutions to overcome ESG disclosure challenges.

| Challenge/reason | Solution |
|---|---|
| **Challenge:** Unsatisfactory level of transparency.<br>**Reason:** the lack of detailed information covering a mining company's all sustainability approaches through each individual mineral supply chain [134]. | • Collaboration with third parties such as Towards Sustainable Mining (TSM) and the Initiative for Responsible Mining Assurance (IRMA) to improve their ESG performances disclosure [10].<br>• Putting more focus on disseminating their specific actions regarding each aspect of SDGs [10]. |
| **Challenge:** Difficulties facing investors, regulators, and other stakeholders in evaluating ESG practices across companies.<br>**Reason:** the existence of different fixed values and principles included in companies' reports giving rise to a variety of standards [135]. | • Standardization of the sustainability report.<br>• The implication of Industry 5.0 technologies to enrich ESG disclosure [133]. |
| **Challenge:** Adopted falsifying behaviors known as greenwashing.<br>**Reasons:** The direct positive influence of credible ESG performance on attracting financial benefits and capital and the cost of the lack of dedication to the legislation enforcing social welfare and environmental conservation [136]. | • Applying green financial policies such as green credit policies to ease the financial pressure on companies and enable them to attract capital and act based on ESG criteria, and consequently entice investors [137]. |
| **Challenge**: Insufficient performance improvements regarding GHG emissions and water usage reduction, and waste recycling [138].<br>**Reasons:** The dearth of applied techniques to reduce GHG emissions [138], inadequate considerations to the importance of decoupling approach to detach the relationship between the water consumption and mining industry's development [139], and the low level of involvement of waste recycling in gross domestic production [140]. | • Evaluating the ESG complexities at a local level, coupled with analyzing local historical mine sites, to create potential future scenarios necessary to deal with uncertainties [141].<br>• Devotion to legislation regarding social and environmental impacts and risk assessment implementation [142].<br>• Creation and integration of ecosystematic innovations into the mining industry to dynamically evaluate and enhance the social, governmental, political, economic, and environmental capabilities of the sector [143,144]. |

United States, Russia, Australia, China, and India [145]. Oil and natural gas reserves mostly concentrate in Russia and Iran [146,147]. The soaring demand for battery minerals essential for decarbonization has altered the global players in geopolitics competitions [148]. By way of illustration, 44 % and 22 % of the global lithium reserves are in Chile and Australia respectively. The DRC supplies 70 % of the global cobalt. Meanwhile, Indonesia for nickel, Chile for copper, and China for graphite and rare earth magnets (used in EVs' motors) are the worldwide biggest mine producers [149].

The world has recognized that China dominates the value chains of EV batteries [148]. In the phase of processing of copper, lithium, manganese, cobalt, graphite, and REEs, China has the highest shares [10,12]. Additionally, the world's largest battery cell manufacturer, Contemporary Amperex Technology Co., Limited, is located in China, the country that is also the largest hub for battery recycling-with a capacity that is 1.5 times larger than the combined total of European countries [10]. In contrast, the European Union is highly dependent on battery raw materials imports. 78 % of its lithium comes from Chile, DRC provides 68 % of its cobalt need, and natural graphite export from China supplies 47 % of European countries' demand. In addition, the materials that are mined in these countries are exported, for example, cobalt to Finland and lithium to Portugal, to be refined [150].

The unequal distribution of battery minerals value chains, the changes in government policies and regulations, state relations, and the social, economic, and environmental factors all lead to geopolitical instability which increases the risks of supply disruption [151]. Table 4 lists some examples clarifying the vulnerability of battery supply chains to different issues.

In 2022, the IEA Critical Minerals Policy Tracker identified more than 100 new policies decreed across the world [159]. The common goal of those policies is to break the geopolitical and geological domination in the supply of battery minerals, and finally to reach a protected, widened, sensibly priced, and socially and environmentally friendly supply of those minerals. The taken initiatives vary from country to country determined by their positions in the supply chains of battery minerals. Table 5 illustrates the strategies adopted by six countries under specific initiatives.

There are of course other countries with their own specific solutions. Examples are Indonesia banning the export of nickel ores to develop domestic processing [166] and Korea and Japan implementing offtake agreements and stockpiling mechanism to decrease the influence of the future potential risks to the sustainability of their supply chains [10].

The aim of those adopted approaches is to minimize the supply disruptions while maximizing the ESG standards to catalyze this green transition. However, one initiative that has garnered the interest of commentators is the US-created MSP. Considering the countries [160] engaged into this partnership-just Western developed countries, Korea, and Japan - there are concerns over the possibility of trade bloc formation and more geopolitical conflicts due to political confederation [167]. With exclusion of China that is dominant in many stages of battery supply chain and the absence of resource-rich countries such as Indonesia, Philippines, Chile, and Peru, the feasibility of this partnership to meet the escalating demand is a controversial issue [168]. More analyses are needed to gain a comprehensive understanding of the gaps and consequences of this partnership which is also likely to result in a new set of geopolitical conflicts.

**Table 4**
Historical cases resulting in supply disruptions.

| Issue | Consequence |
|---|---|
| Nationally precarious political economy | Political instability in DRC between January 2016 and May 2018 disrupting global cobalt supply [152,153]. |
| State relations | China's embargo on exporting REEs to Japan in the fall of 2020 [7]. |
| | Disturbed supply of aluminum and nickel produced in Russia due to the invasion of Ukraine by Russia and the imposed sanctions [154]. |
| Global incident | The suspension of more than 275 mining operations across the world until July 2020 due to the COVID-19 pandemic [155–157]. |
| Regulation changes | Restrict environmental standards lie down by China in 2010 as a criterion to be able to get REEs export permits [158]. |

**Table 5**
Taken strategies to safeguard the supply of battery minerals.

| Strategy | Country | Initiative/taken action |
|---|---|---|
| Resource Diversification | USA | Mineral Security Partnership (MSP): Trade agreements with reliable partners to invest in new mines in different resource-rich regions [160] |
| Bureaucratic strains rearrangement | European countries | Critical Raw Materials Act: Easing the permission processes for extraction, processing, and recycling while upholding social and environmental standards [161] |
| Nationalize supply chains | Canada | Canada's Critical Minerals Strategy: Promoting the competitiveness and capacities of all stages of battery supply chains in the country accompanied with clean technologies integration, and consequently enticing more international investors [162]. |
| Development of skilled workforce | Australia | Australia's Critical Minerals Strategy: Strategic planning to train and entice professionals to amplify the supply chain [163]. |
| Improving security mechanism | U.K. | UK Critical Minerals Intelligence Center: Analyzing and foreseeing the supply and demand dynamics and potential risks through providing independent and fair data [164]. |
| Qualifying mining policies | Chile | National Mining Policy: fostering environmental and social criteria through qualified governance system [165]. |

### 3.4. Material supply from secondary resources

There is a rapidly growing focus on the necessary technological and knowledge advancements in the field of EV battery recycling. Based on the IEA [12] report, the total recycling amount of copper, lithium, nickel, and cobalt by 2040 could decrease the demand for the extraction of mentioned minerals from their primary resources by approximately 10 %. Governments, practitioners, and manufacturers put a high value on the reuse and recycling of battery minerals [169] to alleviate the pressure on primary resources, sustain the supply of battery minerals, as well as to tackle specific environmental challenges (e.g., the release of toxic gases, and the possibility of explosion) caused by the discarded spent batteries [170].

The trend of reuse considerably contributes to decreasing the environmental impacts of EOL batteries both in the short- and medium-terms. Reuse, the second-life application, is to disassemble and repurpose spent EV batteries and use them in renewable energy technologies as 80–85 % of their original energy capacity still remains [171]. After the reuse process, spent batteries having undesired performance can be recycled to extract the valuable minerals and metals [172].

There are different approaches to recover metals and minerals from spent batteries. Pyrometallurgical recovery is the most common method. The drawbacks of this techniques are, for example, high energy consumption (e.g., 0.053 kWh for per Kg of a certain LIB during smelting) and toxic gas emissions (e.g., halogens, dioxins, and furans), which will be even more serious in the growing number of EOL batteries (11 million metric tons by 2030) in the near future [173–175]. Despite having high recovery efficiency, the hydrometallurgical method has many disadvantages including more complex processesand the high cost of chemicals and wastewater treatment [173,176].

There are novel technologies that are aimed at reducing the cost and energy consumption through regenerating functional components from waste LIBs. For example, by means of including direct repair and regeneration of cathode and functional materials in a closed-loop system which is illustrated in Fig. 4 [177,178]. There are still some challenges to these unconventional approaches that need to be addressed. Further research should be done to systematically evaluate the economic benefits, facility costs, energy consumption, labor cost, and environmental impacts at an industrial level. Additionally, whether regenerated cathode materials can have the required potential to be used in new batteries must also be examined [179].

While putting efforts to keep all the materials in the circle, the physical limitations should be considered to derive a realistic solution. According to the second law of thermodynamics, creating a perfectly closed loop of materials is impossible since the generation of waste and unwanted products cannot be eradicated. Recycling efficiency is influenced by the combination of and complicated interaction between the materials in any product. In addition to the current technical challenges towards creating closed-loop recycling systems, it is worth mentioning that the cyclic flow of the battery minerals and raw materials cannot result in a sustainable output alone. The economic value of metals is insufficient to compensate the significantly high energy and environmental costs of reversing the materials flow, or effectively, reversing entropy [182–184]. The final aim should be to minimize waste generation, energy consumption, and cost while reducing the exploitation of primary resources.

To facilitate cost-effective, green, and closed-loop recycling systems, the following actions are paramount.

- A standards-based collaboration between manufacturers and recyclers to facilitate material recovery and reduce cost and environmental and health impacts [185,186];
- Legislation governing EOL battery collection in an environmentally friendly and economic way, from transport, handling, discharging to pre-treatment [187,188];
- Technology and environmental considerations favoring the recovery of all metals and component materials (e.g., electrolytes, separators, and carbon anodes) in a closed-loop recycling scheme [189];
- Technological advancements to minimize pollutants created during the spent battery recycling, which endanger the environment and human health. For example, the pollutants emitted from electrolytes of disassembled batteries (e.g., hydrogen fluoride, phosphorus pentafluoride, and phosphoryl fluoride) [187,190];
- Energy, water, and chemical consumption reduction, renewable energy integration, green chemicals exploitation and recycling [191]; and
- Formal worker protection from hazardous activities (e.g., battery dismantling) in battery recycling [192].

Different countries have implemented different measures to improve their battery recycling sectors. In China, battery manufacturers, based on a provisional measure, have to create the closed loop of batteries [10]. In European countries, by 2030, the recycled resources should account for 15 % of the annual consumption [161]. The US Department of Energy has provided financial support to develop progressive techniques for waste batteries' collection and treatment [193]. Despite these policies, there is a substantial gap in the promotion of circular recycling systems. Battery passports [194] and a globally available battery life cycle sustainability assessment (LCSA) dataset network [185] are considered crucial to create a solid foundation for sustainable recycling mechanisms. From environmental, social, economic, and technical aspects, they provide traceable and transparent flow of information about the entire battery value chains. This globally available information hub provides broad knowledge about efficient recycling practices and consequently opens space for more required improvements.

### 3.5. Diversification and shifts in mineral and elemental requirements

One promising solution to the EVs' susceptibility to the material supply risks is to diversify battery chemistry. For example, cobalt has a high risk of supply disruption since it is considerably extracted as a by-product of nickel and copper production, giving rise to the high cost of cobalt production. Additionally, considerable portion of global cobalt comes from the DRC that witnesses geopolitical instability and tough working conditions [195]. Owing to these challenges and to increase the battery energy density, the market demand for alternative batteries including lithium nickel manganese cobalt oxide (NMC) batteries with 532 NMC (5 parts nickel, 3 parts manganese, and 2 parts cobalt) and 622 NMC cathode chemistries has surged [196].

Another battery element having the potential of disrupting the battery supply chain is graphite. Graphite has two different kinds including natural and synthetic graphite. In comparison with its demand level in

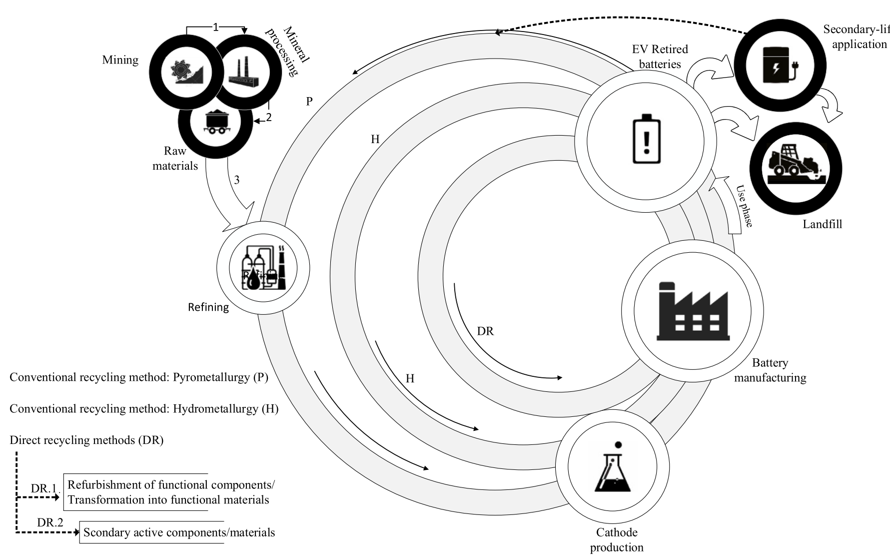


**Fig. 4.** The framework for the closed-loop battery recycling system (modified after Argonne National Laboratory [180] and Neumann et al. [181].

2018, the global demand for graphite is likely to increase by 500 % by 2050. China has a dominant market share of 79 % for natural graphite, and 90 % of synthetic-graphite anode production [197]. Although currently Europe has only a 3 % share of global graphite, there are several projects under development in European countries. For instance, the battery minerals company "Talga" will start to extract graphite from the Niska south deposit at its Vittangi graphite project in Sweden and refine the graphite into coated anode for LIBs [198]. Another graphite project in Europe is the "Woxna" mining project in Sweden [199].

The benefits that synthetic graphite brings to the performance of batteries have led the world to put an effort to replace unequally distributed natural graphite with synthetic graphite as an anode. Synthetic graphite offers a maximum reversible capacity, optimized power energy, and upper-level cycling lifespan [200–202]. Another novel approach is to replace graphite with silicon which has a high theoretical capacity, plentiful resources, and a high safety level. The drawbacks of this approach are insufficient electrical conductivity and significant volume expansion [203].

Furthermore, lithium scarcity and concomitantly its increasing cost have created a niche for sodium-ion batteries to at least co-exist with LIBs in the BEV market. A significant virtue of this battery is that in their production, manganese and iron can be substitutions for cathode materials including cobalt and nickel, which considerably lowers battery cost [204]. Lithium iron phosphate batteries have become one of the most prominent EV batteries due to their high safety, low cost, and long-life cycle [205] in spite of their lower energy capacities [206].

Moreover, research is ongoing to utilize vanadium in the cathode of EV batteries due to its high capacity, energy density, suitable safety, and low cost. This cathode material has some drawbacks that impede its commercialization (e.g., weakening the battery's cycle count, rated capacity, and electrical conductivity) [207]. Overall, in addition to their economic feasibility [196] and performance quality [206], each alternative battery's environmental and social consequences during production, use, storage, repurposing, and recycling phases [208] should be analyzed. Over time, the market will be the determinant for the success of alternative battery chemistries.

## 4. Pragmatic options and pathways towards the future

Since 1990 until today, the increase in GHG emissions has been 50 %, which heightens the need to reduce emissions [209] through taking governmental, organizational, regional, and individual actions [210]. Extensive technological changes, which are underpinned by both regulatory initiatives and improved governance capabilities, are imperative to attain this global demand [211]. There are different approaches towards mitigating climate change that can be split into two categories including innovative technologies and developed technologies. The former includes BEVs, nuclear fission, geoengineering, and carbon sequestration etc. The latter comprises conventional technologies and their associated facilities that are upgraded and transformed, such as improving the energy efficiency of ICEVs [211,212]. The maturity, carbon and cost reduction potential, economic achievement, social consequences, ecological impacts, and uncertainty are the factors that should be considered when analyzing each innovative and upgraded technology [211].

Among the mentioned innovative technologies, BEVs have encountered numerous uncertainties that are mostly formed by geological factors and should not be neglected when assessing to what extent they can contribute to reducing global GHG emissions. One factor that leads the road transport electrification to meet the net-zero goals is its global adoption and not just by certain countries. This trend necessitates new infrastructure development, particularly in the Global South (charging and renewable energy infrastructures), the creation of new policies and regulations supporting EVs, considerable investments in research projects and other associated technologies. There are many countries such as India and Nepal that are struggling to take their places in this new market due to the lack of mentioned prerequisites [213,214]. Additionally, the energy mix and availability of renewable energy resources are the main contributors to the EV value chain carbon footprints [215]. Uncertainty about the sustainability of battery mineral supply chains which is vulnerable to ESG, and economic risks is another issue threatening the growth of the EV market, not to mention the risk of raw materials shortages used for not only battery production but also other green technologies, including dual-use materials for the military [44].

Furthermore, the discrepancy between the development of oil, gas, and coal resources and the goal of global warming mitigation is relatively overlooked [216]. There is a clear contradiction between fossil fuel demand and supply sides. The highest portion of 2020 investments in fuel supply belonged to fossil fuels [217], which carries the risk of repayment to investors provided that the production of fossil fuel stops. Moreover, many industries, such as agriculture (via fertilizers and other petrochemicals) and people are highly dependent on this industry. This aspect strongly affects developing and underdeveloped nations. The energy usage in many underdeveloped nations is still rising and heavily dependent on dense energy resources like oil and gas, and it is difficult to argue that human living conditions should be capped to limit global warming on a much longer timescale. Considering these two important issues, focusing just on the environmental aspects of fossil fuel consumption, and undermining the human rights and investment aspects of international law regulating the production side of fossil fuels and their associated challenges is not a practical pathway to reaching the goal of green transition [218]. Finally, all risks and challenges should be considered holistically in a systematic manner to realize a regretless green transition. Resilience thinking should provide the foundation for any pathway to be able to predict, innovate, improve knowledge, and move on in the force of unexpected changes.

## 5. Summary and outlook

EVs are perceived as a potential solution to reduce $CO_2$ emissions from the transport sector. The global journey towards actual green road transport is fraught with multifaceted challenges since goal conflicts are inherent in all current approaches. This study provides a comprehensive review about the measures that have been implemented by governments, regulatory agencies, automotive industry, and all the other stakeholders involved in the battery value chain. The driving forces behind those measures are evaluated focusing on the challenges of land use conflicts, intensive energy requirement for battery manufacturing and charging, stumbling blocks in the supply of battery minerals form primary resources, difficulties in battery recycling and tailings reprocessing, and battery chemistry diversification.

In the light of conducted analyses, it can be concluded that although there is significant progress on social and environmental protection actions during this transition, more technological efforts, knowledge advancement, investments, and overarching regulations are required. Still the high ESG risks such as GHG emissions and water withdrawal in the whole battery value chains specially in resource-rich countries, are the sign of the existence of the gaps in current policies and approaches. There is a need for more innovation in the mining industry. Furthermore, formulating a comprehensive framework to dynamically evaluate and enhance the social, governance, political, economic, and environmental capabilities of the national and international institutions concerning the green transition is required.

Despite the importance of renewable energy integration into the battery value chain, this approach further competes for energy minerals and metals and is encumbered by the lack of technology and effective local governance and economic differentials across countries. Current geopolitical tensions have motivated the import dependent countries – mostly developed countries-to secure their sustainable supply. Although globally collective actions, competition, and power redistribution are perceived as the foundation for this green transition, these elements are not considered in developed countries, since the actions they take serve their national securities.

Moreover, closed-loop recycling system and mining wastes and tailings reprocessing are the promising approaches to lessening the pressure on primary resources. To succeed in these measures, in addition to metallurgical knowledge advancement and technological improvements, globally available transparent data regarding closed-loop recycling practices and the availability and recoverability of secondary resources are required. In addition, although diversification of battery chemistry is an effective solution, the widespread commercialization of the batteries with new chemistries needs more time.

This review is not without limitations on account of its scope. Through focusing on the EV battery value chain, the factors obstructing the road transport decarbonization have been evaluated. Reductive studies in the future could analyze the supply chain of each individual battery mineral, whereas system-type studies could focus on interactions of geopolitical players, industry and governance, large-scale mining and artisanal and small-scale mining, and the market and ESG frameworks. Such studies are important to develop a deeper and broader understanding of the risks endangering the supply sustainability of battery minerals at the regional and global levels.

## CRediT authorship contribution statement

**Anahita Jannesar Niri**: Conceptualisation, investigation, and writing – original draft. **Gregory A. Poelzer**: Investigation, and writing–review and editing. **Steven E. Zhang**: Investigation and writing– review and editing. Jan Rosenkranz: Writing– review and editing. **Maria Pettersson**: Writing– review and editing. **Yousef Ghorbani**: Conceptualisation, Funding, investigation, and writing – original draft.

## Ethical approval

This study does not contain any studies with human participants or animals performed by any of the authors.

- All authors agree with the submission.
- The manuscript is original and solely submitted to this journal.

## 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

No data was used for the research described in the article.

## Acknowledgments

This study is part of Clean-Mineral project (***Climate friendly mineral supply chains in transition to the green economy***), for which funding was provided by Formas - A Swidish Research Council for Sustainable Development (Formas dnr 2021–02439).

## References

[1] Olabi AG, Wilberforce T, Abdelkareem MA. Fuel cell application in the automotive industry and future perspective. Energy J 2021;214:118955. https://doi.org/10.1016/j.energy.2020.118955.
[2] Mathivathanan D, Kannan D, Haq AN. Sustainable supply chain management practices in Indian Automotive industry: a multi-stakeholder view. Resour Conserv Recycl 2018;128:284–305. https://doi.org/10.1016/j.resconrec.2017.01.003.
[3] Pison G. World population: 8 billion today, how many tomorrow? Population and societies 2022;604(9):1–4. https://doi.org/10.3917/popsoc.604.0001.
[4] Ritchi H, Roser M, Rosado P. $CO_2$ and greenhouse gas emissions. Our World in Data. 2020. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions/. [Accessed 8 January 2023].
[5] Hung CR, Völler S, Agez M, Bettez GM, Strømman AH. Regionalized climate footprint of battery electric vehicles in Europe. J Clean Prod 2021;322. https://doi.org/10.1016/j.jclepro.2021.129052.
[6] Colarullo H, Thakur J. Second-life EV batteries for stationary storage applications in local energy communities. Renew Sustain Energy Rev 2022;169. https://doi.org/10.1016/j.rser.2022.112913.
[7] Nakano J. The Geopolitics of critical minerals supply chains. Center for strategic and international studies (CSIS). Energy security and climate change program. 2021. https://www.csis.org/analysis/geopolitics-critical-minerals-supply-chains.
[8] Bhutada G. Charted: Lithium production by country (1995-2020). Visual Capitalist Organization 2020. https://www.visualcapitalist.com/sp/charted-lithium-production-by-country-1995-2020/;2022. [Accessed 8 January 2023].
[9] Future Battery Industries Cooperative Research Centre. The governance of battery value chains: security, sustainability, and Australian policy options. 2019. https://fbicrc.com.au/wp-content/uploads/2020/05/PU-141-Energy-Report-WEB.pdf.
[10] International Energy Agency. Critical minerals market review. 2023. https://www.iea.org/reports/critical-minerals-market-review-2023.
[11] European Commission. Responsible and sustainable sourcing of batteries raw materials. Joint research Center (JRC); 2020. https://op.europa.eu/en/publication-detail/-/publication.
[12] International Energy Agency. The role of critical minerals in clean energy transition. 2021. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.
[13] International Resource Panel. Resource efficiency and climate change: material efficiency strategies for a low-carbon future. Nairobi, Kenya: United Nations Environment Programme; 2020. https://www.resourcepanel.org/file/1966/download?token=dNgPqfZE.
[14] Kowalska IJ. Towards the reuction of $CO_2$ emissions. Paths of pro-ecological transformation of energy mixes in Europe countries with an above-average share of coal in energy consumption. Res Pol 2022;77:102701. https://doi.org/10.1016/j.resourpol.2022.102701.
[15] Richardson DB. Electric Vehicles and the electric grid: a review of modeling approaches, impacts, and renewable energy integration. Renew Sustain Energy Rev 2013;19:247–54. https://doi.org/10.1016/j.rser.2012.11.042.
[16] Hawkins TR, Gausen OM, Strømman AH. Environmental impacts of hybrid and electric vehicles-a review. Int J Life Cycle Assess 2012;17:997–1014. https://link.springer.com/article/10.1007/s11367-012-0440-9.
[17] Ellingsen LA-W, Hung CR. Research for TRAN Committee – resources, energy, and lifecycle greenhouse gas emission aspects of electric vehicles. Brussels: European Parliament. Policy Department for Structural and Cohesion Policies; 2018. https://op.europa.eu/en/publication-detail/-/publication/ea970289-2806-11e8-ac73-01aa75ed71a1/language-en.
[18] Tan KM, Yong JY, Ramachandaramurthy VK, Mansor M, The J, Guerrero JM. Factors influencing global Transportation electrification: comparative analysis of electric and internal combustion engine vehicles. Renew Sustain Energy Rev 2023:184. https://doi.org/10.1016/j.rser.2023.113582.
[19] Pichler M, Krenmayr N, Schneider E, Brand U. EU industrial policy: between modernization and transformation of the automotive industry. Environ Innov Soc Transit 2021;38:140–52. https://doi.org/10.1016/j.eist.2020.12.002.
[20] Vaz CR, Raunen TRS, Lezana ÁGR. Sustainability and innovation in the automotive sector: a structured content analysis. Sustainability 2017;9(6). https://doi.org/10.3390/su9060880.
[21] Capgemini Research Institute. Sustainability in automotive: from ambition to action. 2020. https://prod.ucwe.capgemini.com/wp-content/uploads.
[22] Jiang HD, Xue MM, Liang QM, Masui T. How to demand-side policies contribute to the electrification and decarbonizatio of private transportation in China? A CGE-based analysis. Technol Forecast Soc Change 2022;175:121322. https://doi.org/10.1016/j.techfore.2021.121322.
[23] Bohnsack R, Kolk A, Pinkse J, Bidmon CM. Driving the electric bandwagon: the Dynamics of incumbents' sustainable development. Bus Strat Environ 2019;29:727–43. https://doi.org/10.1002/bse.2430.
[24] Ibrahim A, Jiang F. The electric vehicle energy management: an overview of the energy system and related modeling and similation. Renew Sustain Energy Rev 2021;144:111049. https://doi.org/10.1016/j.rser.2021.111049.
[25] Kang J, Ng TS, Su B, Milovanoff A. Electrifying light-duty passenger transport CO2emissions reduction: a stochastic-robust input-output linear programming model. Energy Econ 2021;104:105623. https://doi.org/10.1016/j.eneco.2021.105623.
[26] Mohammadzadeh N, Zegordi SH, Kashan AH, Nikbakhsh E. Optimal government policy-making for electric vehicle adoption using the total cost of ownership under the budget constraint. Sustain Prod Consum 2022;33:477–507. https://doi.org/10.1016/j.spc.2022.07.015.
[27] Zhang X, Liang Y, Yu E, Rao R, Xie J. Review of electric vehicles policies in China: conten summary and effect analysis. Renew Sustain Energy Rev 2017;70:698–714. https://doi.org/10.1016/j.rser.2016.11.250.
[28] Wang A, Xu J, Zhang M, Zhai Z, Song G. Emission and fuel consumption of a hybrid electric vehicle in real-world metropolitan traffic conditions. J. App. Eng 2022;306:118077. https://doi.org/10.1016/j.apenergy.2021.118077.
[29] International Energy Agency. Global EV Outlook. https://www.iea.org/reports/global-ev-outlook-2023; 2023.
[30] Kaviani MA, Tavana M, Kumar A, Michnik J, Niknam R, Elaine Aparecida Regiani de Campos. An integrated framework for evaluating the barriers to successful

implementation of reverse logistics in the automotive industry. J Clean Prod 2020;727. https://doi.org/10.1016/j.jclepro.2020.122714.
[31] Natural Resource Governance Institute. Sustainable drive sustainable supply. Priorities to improve the electric vehicle battery supply chain. 2020. https://resourcegovernance.org/sites/default/files/documents/sustainable-drive-sustainable-supply-priorities-to-improve-the-electric-vehicle-battery-supply-chain.pdf.
[32] Jasinski D, Meredith J, Kirwan K. A comprehensive framework for automotive sustainability assessment. J Clean Prod 2016;135:1034–44. https://doi.org/10.1016/j.jclepro.2016.07.027.
[33] Globaldata ESG. (environmental, social, and governance) in automotive-thematic research. 2021. https://www.globaldata.com/store/report/esg-in-automotive-industry-theme-analysis/.
[34] Gohoungodji P, N'Dri BA, Latulippe JM, Matos ALB. What is stopping the automotive industry from going green? A systematic review of batteries to green innovation in the automotive industry. J Clean Prod 2020;277:123524. https://doi.org/10.1016/j.jclepro.2020.123524.
[35] Hancock L, Ralph N, Ali SH. Bolivia's lithium frontier: can public private partnership deliver a minerals boom for sustainable development. J Clean Prod 2018;178:551–60. https://doi.org/10.1016/j.jclepro.2017.12.264.
[36] Government Accountability Office. U.S. Disclosure of environmental, social, and governance factors and options to enhance them. 2020. https://www.gao.gov/assets/710/707967.pdf.
[37] International Resource Panel. Mineral Resource governance in the 21st century. Gearing extractive industries towards sustainable development. Nairobi, Kenya: United Nations Environment Programme; 2020. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century.
[38] Khaled R, Ali H, Mohamed EKA. The sustainable development goals and corporate sustainability performance: mapping, extent and determinants. J Clean Prod 2021;311:127599. https://doi.org/10.1016/j.jclepro.2021.127599.
[39] Chen G, Xu J, Qi Y. Environmental (de)centralization and local environmental governance: evidence from a natural experiment in China. China Econ. Rev 2022; 72. https://doi.org/10.1016/j.chieco.2022.101755.
[40] Glavas D, Grolleau G, Mzoughi N. Greening the greenwashers – how to push greenwashers towards more sustainable trajectories. J Clean Prod 2023:382. https://doi.org/10.1016/j.jclepro.2022.135301.
[41] Pei-yi Yu E, Luu BV, Chen CH. Greenwashing in environmental, social and governance disclosures. Res Int Bus Finance 2020;52. https://doi.org/10.1016/j.ribaf.2020.101192.
[42] Liu C, Song Y, Wang W, Shi X. The governance of manufacturers' greenwashing behaviors: a tripartite evolutionary game analysis of electric vehicles. Appl Energy 2023:333. https://doi.org/10.1016/j.apenergy.2022.120498.
[43] Dall-Orsoletta AD, Ferreira P, Dranka GG. Low-carbon technologies and just energy transition: prospects for electric vehicles. J. Ener. Con. Man 2022;16: 100271. https://doi.org/10.1016/j.ecmx.2022.100271.
[44] Gebhardt M, Beck J, Kopyto M, Spieske A. Determining requirements and challenges for a sustainable and circular electric vehicle battery supply chain: a mixed-methods approach. Sustain Prod Consum 2022;33:203–17. https://doi.org/10.1016/j.spc.2022.06.024.
[45] Marcos JT, Scheller C, Godina R, Spengler TS, Carvalho H. Sources of uncertainty in the closed-loop supply chain of lithium-ion batteries for electric vehicles. CLSCN 2021;1:100006. https://doi.org/10.1016/j.clscn.2021.100006.
[46] Ikome JM, Laseinde OT, Katumba MGK. The future of the automotive manufacturing industry in developin nations: a case Study of its sustainability based on South Africa's paradigm. Procedia Comput Sci 2022;200:1165–73. https://doi.org/10.1016/j.procs.2022.01.316.
[47] Heuveln KV, Ghotge R, Annema JA, Bergen EV. Factors influencing consumer acceptance of vehicle-to-grid by electric vehicles drivers in The Netherlands. Travel Behav Soc 2021;24:34–45. https://doi.org/10.1016/j.tbs.2020.12.008.
[48] Ramani V, Ghosh D, Sodhi MS. Understanding systemic disruption from Covid-19-induced semiconductor shortage for the auto industry. Omega 2022;113: 102729. https://doi.org/10.1016/j.omega.2022.102720.
[49] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2012;17(1). https://onlinelibrary.wiley.com/doi/full/10.1111/j.1530-9290.2012.00532.x.
[50] Jajja MS, Hassan SZ, Asif M, Searcy C. Manufacturing value chain for battery electric vehicles in Pakistan: an assessment of capabilities and transition pathways. J Clean Prod 2021;328:129512. https://doi.org/10.1016/j.jclepro.2021.129512.
[51] Ternel C, Bouter A, Melgar J. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. Transp Res D Transp Environ 2021;97:102897. https://doi.org/10.1016/j.trd.2021.102897.
[52] Hasan A, Osman A, Al-Muhtaseb AH, Al-Rawashdeh H, Abu-jrai A, Ahmed R, Gomaa MR, Deka TJ, Rooney DW. An experimental study of engine characteristics and tailpipe emissions from modern DI diesel engine fuelled with methanol/diesel blends. Fuel Process Technol 2021;220:106901. https://doi.org/10.1016/j.fuproc.2021.106901.
[53] Yu J, Dong X, Song Y, Zhang Y, Zhang H, Yang X, Xu Z, Liu Y. Energy efficiency optimization of a compound coupled hydromechanical transmission for heavy-duty vehicles. Energy 2022;252:123937. https://doi.org/10.1016/j.energy.2022.123937.
[54] Der A, Dilger N, Kaluza A, Creighton C, Kara S, Varley R, Herrmann C, Thiede S. Modelling and analysis of the energy intensity in polyacrylonitrile (PAN) precursor and carbon fiber manufacturing. J Clean Prod 2021;303:127105. https://doi.org/10.1016/j.jclepro.2021.127105.
[55] Liu J, Daigo I, Panasiuk D, Dunuwila P, Hamada K, Hoshino T. Impact of recycling effect in coparative life cycle assessment for materials selectrion-A case study of light weighting vehicles. J Clean Prod 2022;349:131317. https://doi.org/10.1016/j.jclepro.2022.131317.
[56] Serrenho AC, Norman JB, Allwood JM. The impacts of reducing car weight on global emissions: the future fleet in Great Britain. Philos. Trans. Royal Soc 2017; 13:375. https://doi.org/10.1098/rsta.2016.0364.
[57] Kazancoglu Y, Ozbiltekin-Pala M, Ozkan-Ozen YD. Prediction and evaluation of greenhouse gas emissions for sustainable road transport within Europe. Sustain Cities Soc 2021;70:102924. https://doi.org/10.1016/j.scs.2021.102924.
[58] Baker S. Sustainable development: between reformist change and radical transformation. In: Bornemann B, Knappe H, Nanz P, editors. The routledge handbook of democracy and sustainability. first ed. Routledge; 2022. https://doi.org/10.4324/9780429024085.
[59] Brink SVD, Kleijn R, Tukker A, Huisman J. Approaches to responsible souring in mineral supply chains. Resour Conserv Recycl 2019;145:389–98. https://doi.org/10.1016/j.resconrec.2019.02.040.
[60] Thatje S. Ethical considerations surrounding deep-sea mining do matter. Trends Ecol Evol 2021;36(8):674–5. https://doi.org/10.1016/j.tree.2021.04.004.
[61] Quebec Propulsion. Lithium-ion battery sector. 2019. https://propulsionquebec.com/wp-content/uploads/2019/09/RAPPORT-BATTERIES-LITHIUM-ION-EN-2.pdf.
[62] Newsroom Toyota. https://pressroom.toyota.com/toyota-selects-north-carolina-greensboro-randolph-site-for-new-u-s-automotive-battery-plant/. [Accessed 29 December 2022].
[63] 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. https://doi.org/10.1016/j.apenergy.2022.119230.
[64] Dall-Orsoletta A, Ferreira P, Dranka GG. Low-carbon technologies and just energy transition: prospects for electric vehicles. Energy Convers Manag 2022;16: 100271. https://doi.org/10.1016/j.ecmx.2022.100271.
[65] Institute for Local Government. Understanding recycling facilities and required permits. 2015. https://www.ca-ilg.org/post/understanding-recycling-facilities-and-required-permits.
[66] Scheidel A, Sorman AH. Energy transition and the global land rush: ultimate drivers and persistent consequences. Global Environ Change 2012;22:588–95. https://doi.org/10.1016/j.gloenvcha.2011.12.005.
[67] Niu H, Wang J, Jing Z, Liu B. Identification and management of land use conflicts in mining cities: a case study of Shuozhou in China. Res Pol 2023;81:103301. https://doi.org/10.1016/j.resourpol.2023.103301.
[68] Anaman R, Peng C, Jiang Z, Liu X, Zhou Z, Guo Z, Xiao X. Identifying sources and transparent routes of heavy metals in soil with different land use around a smelting site by GIS based PCA and PMF. Sci Total Environ 2022;823:153759. https://doi.org/10.1016/j.scitotenv.2022.153759.
[69] Hilson G. An overview of land use conflicts in mining communities. Land Use Pol 2002;19(1):65–73. https://doi.org/10.1016/S0264-8377(01)00043-6.
[70] Kivinen M, Eilu P, Markovaara-Koivisto M. Mineral futures in land-use planning: foresight tools and case studies in Northern Finland. Res Pol 2021;70:101917. https://doi.org/10.1016/j.resourpol.2020.101917.
[71] Zachrisson A, Lindahl KB. Extractive governance and mining conflicts: challenging scalar hierarchies through 'opening up' to local sustainability pathways. Polit Geogr 2023;105:102927. https://doi.org/10.1016/j.polgeo.2023.102927.
[72] Moffat K, Lacey J, Zhang A, Leipold S. The social licence to operate: a critical review. J. For. Res 2016;89(5):477–88. https://doi.org/10.1093/forestry/cpv044.
[73] Chipangamate NS, Nwaila GT, Bourdeau JE, Zhang EZ. Integration of stakeholder engagement practices in pursuit of social licence to operate in a modernising mining industry. Res Pol 2023;85(B). https://doi.org/10.1016/j.resourpol.2023.103851.
[74] Poelzer G, Lindahl KB, Segerstedt E, Abrahamsson L, Karlsson M. Licensing acceptance in a mineral-rich welfare state: critical reflections on the social license to operate in Sweden. Extr Ind Soc 2020;7:1096–107. https://doi.org/10.1016/j.exis.2020.05.008.
[75] Yates FB, Horvath CL. Social license to operate: how to get it, and how to keep it. Pacific Energy Summit; 2013. https://www.nbr.org/publication/social-license-to-operate-how-to-get-it-and-how-to-keep-it/.
[76] Balza LH, Lina MD, Gomez-Parra N, Manano MOE. The unwritten license: the societal SLO in Latin America's extractive sector. Ecol Econ 2023;213:107942. https://doi.org/10.1016/j.ecolecon.2023.107942.
[77] Tran TH, Egermann M. Land-use implications of energy transition pathways towards decarbonization-comparing the footprints of Vietnam, New Zealand and Finland. Energy Pol 2022;166:112951. https://doi.org/10.1016/j.enpol.2022.112951.
[78] Zhang N, Zheng J, Song G, Zhao H. Regional comprehensive environmental impact assessment of renewable energy system in California. J Clean Prod 2022; 376:134349. https://doi.org/10.1016/j.jclepro.2022.134349.
[79] Sessa MR, Russo A, Sica F. Opinion paper on green deal for the urban regeneration of industrial brownfield land in Europe. Land Use Pol 2022;119: 106198. https://doi.org/10.1016/j.landusepol.2022.106198.
[80] Zhou D, Wang H, Wang M. Does local government competition affect the dependence on polluting industries? Evidence from China's land market. J Environ Manag 2023;325:116518. https://doi.org/10.1016/j.jenvman.2022.116518.

[81] Shafique M, Luo X. Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective. J Environ Manag 2021;303:114050. https://doi.org/10.1016/j.jenvman.2021.114050.
[82] Yuan C, Deng Y, Li T, Yang F. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CRIP Ann 2017;66:53–6. https://doi.org/10.1016/j.cirp.2017.04.109.
[83] Schönemann M. Multiscale simulation approach for battery production systems. In: Herrmann C, Kara S, editors. SPLCEM (Sustainable production, life cycle engineering and management) book series; 2017. https://link.springer.com/book/10.1007/978-3-319-49367-1.
[84] Silva GV, Thomitzek M, Abraham T, Herrmann C. Bottleneck reduction strategies for energy efficiency in the battery manufacturing. Procedia CIRP 2021;104:1017–22. https://doi.org/10.1016/j.procir.2021.11.171.
[85] Dunn JB, Gaines L, Kelly JC, Gallagher KG. The significance of Li-ion batteries in electric vehicles life-cycle energy and emissions and recycling role in its reduction. Energy Environ Sci 2015;8:158–68. https://doi.org/10.1039/c4ee03029j.
[86] Romare M, Dahllöf L, IVL Swedish Environmental Research Institute. The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries. Swedish Energy Agency. No. C 243; 2017. https://www.ivl.se/download/18.5922281715bdaebede95a9/1496136143435/C243.pdf.
[87] Kim HC, Wallington TJ, Arsenault R, Ba C, Ahn S, Lee J. Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative Analysis. J. Environ. Sci. Technol 2016;50:7715–22. https://doi.org/10.1021/acs.est.6b00830.
[88] International Energy Agency. World energy outlook 2022. https://iea.blob.core.windows.net/assets/830fe099f; 2022.
[89] Al-shroofy M, Zhang Q, Xu J, Chen T, Kaur AP, Cheng YT. Solvent-free dry powder coating process for low-cost manufacturing of LiNi1/3Mn1/3Co1/3O2 cathods in lithium-ion batteries. J Power Sources 2017;352(1):187–93. https://doi.org/10.1016/j.jpowsour.2017.03.131.
[90] Vogt M, Der A, Khalid U, Cerdas F, Hermann C. Model-based planning of technical building services and process chains for battery cell production. J Clean Prod 2022;370:133512. https://doi.org/10.1016/j.jclepro.2022.133512.
[91] U.S. Department of. Energy. Investing in American energy. Office of policy report. 2023. https://www.energy.gov/sites/default/files/2023-08/DOE%20OP%20Economy%20Wide%20Report_0.pdf.
[92] European Commission. Legislation 130. Official Journal of the European Union; 2023. p. 66. Publications Office (europa.eu), https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L:2023:130:FULL.
[93] Podesta JD. Building a clean energy economy. Inflation reduction act guidebook. The White House Washington; 2023. version 2, https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf.
[94] Mirza N, Naqvi B, Rizvi SKA, Umar M. Fiscal or monetary? Efficiency of regulatory regimes and energy trilemma of the inflation reduction act (IRA). Int Rev Financ Anal 2023;90:102821. https://doi.org/10.1016/j.irfa.2023.102821.
[95] Berger K, Baumgartner RJ, Weinzerl M, Bachler J, Preston K, Schöggl JP. Data requirements and availabilities for a digital battery passport – a value chain actor perspective. Cleaner Production Letters 2023;4:100032. https://doi.org/10.1016/j.clpl.2023.100032.
[96] Thakare S, Rodrigues N, Rawat A, Kumar M, Vyas S, Sharma A, Datta A. Decarbonizing transportation in India: policy framework, charging infrastructure, and impact of electric vehicles on the grid by 2030. New Delhi: The Energy and Resources Institute); 2021. TERI Discussion Paper, https://www.teriin.org/sites/default/files/files/Policy-Framework_Charging-%20Infrastructure_Impact-of-EV.pdf.
[97] Lamedica R, Ruvio A, Falessi P, Maccioni M, Sammartino E, Palumbo M. Power unit architecture in a high-power charging system for EVs. Int J Electr Power Energy Syst 2023;149:109052. https://doi.org/10.1016/j.ijepes.2023.109052.
[98] Hou L, Herrera OE, Mérida W. Charging scheduling and energy management for mobile chargers in a grid-interactive transportation system. J Energy Storage 2023;65:107305. https://doi.org/10.1016/j.est.2023.107305.
[99] Chadha S, Jain V, Singh HR. A review on smart charging impacts of electric vehicles on grid. Mater Today: Proc 2022;63:751–5. https://doi.org/10.1016/j.matpr.2022.05.122.
[100] Carlier M. Number of electric vehicle charging stations in Europe 2020-2022. In: Europe: number of electric vehicle charging stations 2022. Statista; 2023. . [Accessed 2 October 2023].
[101] Conzade J, Nägele F, Ramanathan S, Schaufuss P. Europé's EV opportunity – and the charging infrastructure needed to meet it. Automotive and assembly practice. McKinsey and Company; 2022. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/europes-ev-opportunity-and-the-charging-infrastructure-needed-to-meet-it#/.
[102] Kikhavani MR, Hajizadeh A, Shahirinia A. Charging coordination and load balancing of plug-in electric vehicles in unbalanced low voltage distribution systems. IET Gener, Transm Distrib 2020;14(3):389–99. https://doi.org/10.1049/iet-gtd.2019.0397.
[103] Blasius B, Wang Z. Effects of charging battery electric vehicles on local grid regarding standardized load profile in administration sector. Appl Energy 2018;224:330–9. https://doi.org/10.1016/j.apenergy.2018.04.073.
[104] Bitencourt LA, Borba BSMC, Dias BH, Maciel RS, Dias DHN, Leonardo WO. Electric vehicles charging optimization to improve the insertion considering the Brazilian regulatory framework. J Energy Storage 2019;1:1–13. https://doi.org/10.1002/est2.76.
[105] Bibak B, Mogulkoç HT. A comprehensive analysis of vehicle to grid (V2G) systems and scholarly literature on the application of such systems. Renew. Energy Focus 2021;36:1–20. https://doi.org/10.1016/j.ref.2020.10.001.
[106] Wan Z, Zhu WT, Wang G. PRAC: efficient privacy protection for vehicle-to-grid communications in the smart grid. Comput Secur 2016;62:246–56. https://doi.org/10.1016/j.cose.2016.07.004.
[107] Su W, Rahimi-Eichi H, Zeng W, Chow MY. A Survey on the electrification of transportation in a smart grid environment. IEEE Trans Ind Inf 2012;8(1):1–10. https://doi.org/10.1109/TII.2011.2172454.
[108] Yap KY, Chin HH, Klemes JJ. Solar energy-powered battery electric vehicle charging stations: current development and future prospect review. Renew Sustain Energy Rev 2022;169:112862. https://doi.org/10.1016/j.rser.2022.112862.
[109] Mehrjerdi H. Dynamic and multi-stage capacity expansion planning in microgrid integrated with electric vehicle charging station. J Energy Storage 2020;29:101351. https://doi.org/10.1016/j.est.2020.101351.
[110] International Energy Agency. Global EV outlook 2022. https://iea.blob.core.windows.net/assets/ad8fb04c; 2022.
[111] International Energy Agency. Electric vehicles. 2022. https://www.iea.org/reports/electric-vehicles/. [Accessed 29 December 2022].
[112] Bhutada G. The key minerals in an EV battery. 2022. https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/. [Accessed 8 January 2023].
[113] Iglesias-Émbi M, Valero A, Ortego A, Villacampa M, Vilaró J, Villalba G. Raw material use in a battery electric car – a thermodynamic rarity assessment. Re. Con. Rec 2020;158:104820. https://doi.org/10.1016/j.resconrec.2020.104820.
[114] Valero A, Valero A, Calvo G, Ortego A. Material bottlenecks in the future development of green technologies. Renew Sustain Energy Rev 2018;93:178–200. https://doi.org/10.1016/j.rser.2018.05.041.
[115] Michaux SP. Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels. Geological Survey of Finland (GTK). Report 2021;42. https://doi.org/10.13140/RG.2.2.34895.00160.
[116] Valente RK, Kemp D, Owen JR, Corder GD, Lebre E. Re-thinking complex orebodies: consequences for the future world supply of copper. J Clean Prod 2019;220:816–26. https://doi.org/10.1016/j.jclepro.2019.02.146.
[117] Dehaine Q, Michaux SP, Pokki J, Kivinen M, Butcher AR. Battery minerals from Finland: improving the supply chain for the EU battery industry using a geometallurgical approach. Topical- mineral raw materials. Geological survey of Finland; 2020. https://doi.org/10.5281/zenodo.3938855.
[118] Mends EA, Chu P. Lithium extraction from unconventional aqueous resources – a review on recent technological development for seawater and geothermal brines. J Environ Chem Eng 2023;11(5):110710. https://doi.org/10.1016/j.jece.2023.110710.
[119] Dehaine Q, Tijsseling LT, Glass HJ, Törmänen T, Butcher AR. Geometallurgy of cobalt ores: a review. Miner Eng 2021;160:106656. https://doi.org/10.1016/j.mineng.2020.106656.
[120] Congressional Research Service. Critical minerals in electric vehicle batteries. 2022. https://crsreports.congress.gov/product/pdf/R/R47227.
[121] Gandhi SM, Sarkar BC. Essentials of minerals exploration and evaluation. Elsevier Science; 2016. https://www.sciencedirect.com/book/9780128053294/essentials-of-mineral-exploration-andevaluation#book-description.
[122] Wall F, Rollat A, Pell RS. Responsible sourcing of critical metals. Elements 2017;13:313–8. https://doi.org/10.2138/gselements.13.5.313.
[123] Spuerk S, Drobe M, Lottermoser BG. Evaluating resource efficiency at major copper mines. Min. En 2016;107:27–33. https://doi.org/10.1016/j.mineng.2016.12.005.
[124] Magdalena R, Valero A, Calvo G. Limit of recovery: how future evolution of ore grades could influence energy consumption and prices for nickel, cobalt, and PGMs. Miner Eng 2023;200:108150. https://doi.org/10.1016/j.mineng.2023.108150.
[125] Adrianto LR, Ciacci L, Pfister S, Hellweg S. Toward sustainable reprocessing and valorization of sulfidic copper tailings: scenario and prospective LCA. Sci Total Environ 2023;871:162038. https://doi.org/10.1016/j.scitotenv.2023.162038.
[126] Sarker SK, Haque N, Bruckard W, Bhuiyan M, Pramanik BK. Development of a geospatial database of tailing storage facilities in Australia using satellite images. Chemosphere 2022;303:135139. https://doi.org/10.1016/j.chemosphere.2022.135139.
[127] Tinti F, Kasmaeeyazdi S, Bodenon F, Sparis D. Mining and processing residues. In: Chernoburova O, Chagnes A, editors. 4 – authorization and legal aspects of residue storage and reprocessing. Elsevier: E-publishing; 2023. p. 185–217. https://www.sciencedirect.com/book/9780323951753/mining-and-processing-residues.
[128] Figueiredo J, Vila MC, Matos K, Martins D, Futuro A, Dinis MDL, Góis J, Leite A, Fiúza A. Tailings reprocessing from Cabeço do Pião dam in Central Portugal: a kinetic approach of experimental data. J. Sustain. Min. 2018;17(3):139–44. https://doi.org/10.1016/j.jsm.2018.07.001.
[129] Lèbre É, Stringer M, Svobodova K, Owen JR, Kemp D, Côte C, A-Solar A, Valenta RV. The social and environmental complexities of extracting energy transition metals. Nat Commun 2020;11:4823. https://doi.org/10.1038/s41467-020-18661-9.
[130] Rachidi NR, Nwaila GT, Zhang SE, Bourdeau JE, Ghorbani Y. Assessing cobalt supply sustainability through production forecasting and implication for green energy policies. Res Pol 2021;74:102423. https://doi.org/10.1016/j.resourpol.2021.102423.
[131] Natural Resource Governance Institute. Building a sustainable electric vehicle battery supply chain: frequently asked questions. 2020. https://resourcego

vernance.org/analysis-tools/publications/building-sustainable-electric-vehicle-battery-supply-chain-faqs.
[132] Lèbre É, John R, Owen JR, Corder GD, Kemp D, Stringer M, Valenta RK. Source risks as constraints to future metal supply. Environ Sci Technol 2019;53:10571–9. https://doi.org/10.1021/acs.est.9b02808.
[133] Asif M, Searcy C, Castka P. ESG and industry 5.0: the role of technologies in enhancing ESG disclosure. Technol Forecast Soc Change 2023;195:122806. https://doi.org/10.1016/j.techfore.2023.122806.
[134] Machado MC, Correa VS, Queiroz MM, Costa GC. Can global reporting initiative reports reveal companies' green supply chain management practices. J Clean Prod 2023;383:135554. https://doi.org/10.1016/j.jclepro.2022.135554.
[135] Ivic A, Saviolidis NM, Johannsdottir L. Drivers of sustainability practices and contributions to sustainable development evident in sustainability reports of European mining companies. Discov Sustain 2021;2(17). https://doi.org/10.1007/s43621-021-00025-y.
[136] He X, Jing Q, Chen H. The impacts of environmental tax laws on heavy-polluting enterprise ESG performance: a stakeholder behavior perspective. J Environ Manag 2023;344:118578. https://doi.org/10.1016/j.jenvman.2023.118578.
[137] Lei N, Miao Q, Yao X. Does the implementation of green credit policy improve the ESG performance of enterprises? Evidence from a quasi-natural experiment in China. Econ Modell 2023;127:106478. https://doi.org/10.1016/j.econmod.2023.106478.
[138] Huo D, Sari YA, Kealey R, Zhang Q. Reinforcement learning-based fleet dispatching for greenhouse gas emission reduction in open-pit mining operations. Resour Conserv Recycl 2023;188:106664. https://doi.org/10.1016/j.resconrec.2022.106664.
[139] Li Y, Zhang Y, Yang L, Du F, Sai L, Zhang B. Decoupling analysis of China's mining industrial development and water usage: based on production-based and consumption-based perspectives. J Clean Prod 2023;385:135668. https://doi.org/10.1016/j.jclepro.2022.135668.
[140] Manjenengwa ER, Dorfling C, Tadie M. Development of a conceptual framework to evaluate factors that affect drivers for stakeholder engagement in mine waste management. Res Pol 2023;81:103280. https://doi.org/10.1016/j.resourpol.2022.103280.
[141] Sternberg T, Ahearn A. Mongolian mining engagement with SIA and ESG initiative. Environ Impact Assess Rev 2023;103:107269. https://doi.org/10.1016/j.eiar.2023.107269.
[142] Cole MJ. ESG risks to global platinum supply: a case study of Mogalakwena mine, South Africa. Res Pol 2023;85:104054. https://doi.org/10.1016/j.resourpol.2023.104054.
[143] Muller J. Enabling technologies for industry 5.0 – results of a workshop with Europe's technology leaders. European Commission, Directorate-General for Research and Innovation, Publications Office; 2020. https://data.europa.eu/doi/10.2777/082634.
[144] Balci M, Kumral M. Building an innovation strategy and culture on the structural characteristics of the mining industries. Res Pol 2022;78:102936. https://doi.org/10.1016/j.resourpol.2022.102936.
[145] Venditti B. Which countries have the world'd largest coal reserves. Visual capitalist organization. 2021. ELEMENTS. https://elements.visualcapitalist.com/which-countries-have-the-worlds-largest-coal-reserves/. [Accessed 5 January 2023].
[146] Our World. Data. Oil reserves. https://ourworldindata.org/search?q=Oil++reserves/. [Accessed 5 January 2023].
[147] Our world in data. Gas reserves. https://ourworldindata.org/search?q=natural+gas++reserves. [Accessed 5 January 2023].
[148] Stampatori D, Raimondi PP, Noussan M. Li-ion batteries: a review of a key technology for transport decarbonization. Energies 2020;13:2638. https://doi.org/10.3390/en13102638.
[149] European Parliamentary Research Service. Resilient supply chains in the green transition. 2021. https://www.europarl.europa.eu/RegData/etudes/ATAG/2021/696181/EPRS_ATA(2021)696181_EN.pdf.
[150] Lebrouhi BE, Baghi S, Lamrani B, Schall E, Kousksou T. Critical materials for electrical energy storage: Li-ion batteries. J Energy Storage 2022;55:105471. https://doi.org/10.1016/j.est.2022.105471.
[151] British Geological survey. UK criticality assessment of technology critical minerals and metals. Decarbonization and resource management commissioned report. 2021. https://www.bgs.ac.uk/download/uk-criticality-assessment-of-technology-critical-minerals-and-metals/.
[152] Sovacool KB. The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. Extr Ind Soc 2019;6:915–39. https://doi.org/10.1016/j.exis.2019.05.018.
[153] Decarlo S, Matthews D. More than a pretty color: the renaissance of the cobalt industry. JICE; 2019. https://www.usitc.gov/staff_publications/jice/more_pretty_color_renaissance_cobalt_industry.
[154] Organisation for Economic Co-operation and Development. The supply of critical raw materials endangered by Russia's war on Ukraine. 2022. https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/.
[155] Sun X, Liu G, Hao H, Liu Z, Zhao F. Modeling potential impact of COVID-19 pandemic on global electric vehicle supply chain. J. iScience 2022;25(3):103903. https://doi.org/10.1016/j.isci.2022.103903.
[156] Wen W, Yang S, Zhou P, Gao SZ. Impacts of COVID-19 on the electric vehicle industry: evidence from China. Ren. Sus. En. Rew 2021;144:111024. https://doi.org/10.1016/j.rser.2021.111024.
[157] Zhu Y, Ali SH, Xu D, Cheng J. Mineral supply challenges during the COVID-19 pandemic suggest need for international supply security mechanism. Resour Conserv Recycl 2021:165. https://doi.org/10.1016/j.resconrec.2020.105231.
[158] Shen Y, Moomy R, Eggert RG. China's public policies toward rare earths, 1975–2018. Miner Econ 2020;33:127–51. https://doi.org/10.1007/s13563-019-00214-2.
[159] International Energy Agency. Critical minerals policy tracker. 2022. Paris, https://www.iea.org/reports/critical-minerals-policy-tracker. [Accessed 5 October 2023].
[160] U.S. Department of State. Mineral security partnership. 2023. https://www.state.gov/minerals-security-partnership/. [Accessed 5 October 2023].
[161] Ragonnaud G. Critical raw materials act. European Parliamentary Research Service; 2023. https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747898/EPRS_BRI(2023)747898_EN.pdf.
[162] Wilkinson J. The Canadian critical minerals strategy. 2022. https://www.canada.ca/content/dam/nrcan-rncan/site/critical-minerals/Critical-minerals-strategy Dec09.pdf.
[163] Bogdanich I, Hardcastle B, Donnelly D, Axup K, Manderson K. Australia's critical minerals strategy 2023-2030. 2023. https://www.allens.com.au/insights-news/insights/2023/06/Australias-Critical-Minerals-Strategy-2023-2030/. [Accessed 6 October 2023].
[164] UK Critical Minerals Intelligence Center. https://ukcmic.org/index.html. [Accessed 6 October 2023].
[165] Mining 2050. National mining policy. Public policy report. The ministry of Mining, Government of Chile; 2022. https://www.politicanacionalminera.cl/wp-content/uploads/2022/03/MINING_2050_NATIONAL_MINING_POLICY.pdf.
[166] International Energy Agency. Prohibition of the export of nickel ore. 2022. https://www.iea.org/policies/16084-prohibition-of-the-export-of-nickel-ore. [Accessed 6 October 2023].
[167] Dou S, Xu D, Zhu Y, Keenan R. Critical minerals sustainable supply: challenges and governance. Futures 2023;146:103101. https://doi.org/10.1016/j.futures.2023.103101.
[168] Vivoda V. Friend-shoring and critical minerals: exploring the role of the minerals security partnership. Energy Res Social Sci 2023;100:103085. https://doi.org/10.1016/j.erss.2023.103085.
[169] Yamamoto T, Merciai S, Mogollon JM, Tukker A. The role of recycling in alleviating supply chain risk–Insights from a stock-flow perspective using a hybrid input-output database. Resour Conserv Recycl 2022;185:106474. https://doi.org/10.1016/j.resconrec.2022.106474.
[170] Lv W, Wang Z, Cao H, Sun Y, Zhang Y, Sun Z. A critical review and analysis on the recycling of spent lithium-ion batteries. ACS Sustainable Chem Eng 2018;6:1504–21. https://doi.org/10.1021/acssuschemeng.7b03811.
[171] European Environmental Agency. Electric vehicles from life cycle and circular economy perspectives. 2018. https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle/at_download/file.
[172] Pagliaro M, Meneguzzo F. Lithium battery reusing and recycling: a circular economy insight. Heliyon 2019;5:1866. https://doi.org/10.1016/j.heliyon.2019.e01866.
[173] Latini D, Vaccari M, Langnoni M, Orefice M, Mathieux F, Huisman J, Tongnotti L, Bertei A. A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling. J Power Sources 2022;546. https://doi.org/10.1016/j.jpowsour.2022.231979.
[174] Xu P, Tan DHS, Gao H, Rose S, Chen Z. Encyclopedia of energy storage. In: Cabeza LF, editor. Recycling of Li-ion batteries for electric vehicles, vol. 4. Elsevier: E-Publishing; 2022. p. 98–107. https://doi.org/10.1016/B978-0-12-819723-3.00079-2.
[175] Reinhart L, Vrucak D, Woeste R, Lucas H, Rombach E, Friedrich B, Letmathe P. Pyrometallurgical recycling of different lithium_ion battery cell systems: economic and technical analysis. J Clean Prod 2023;416:137834. https://doi.org/10.1016/j.jclepro.2023.137834.
[176] Chio Y, Rhee SW. Current status and perspectives on recycling of end-of-life battery of electric vehicle in Korea (Republic of). Waste Manage (Tucson, Ariz) 2020;106:261–70. https://doi.org/10.1016/j.wasman.2020.03.015.
[177] Xu R, Xu W, Wang J, Liu F, Sun W, Yang Y. A review on regenerating materials from spent lithium-ion batteries. Molecules 2022;27:2285. https://doi.org/10.3390/molecules27072285.
[178] Sa Q, Gratz E, He M, Lu W, Apelian D, Wang Y. Synthesis of high performance LiNi1/3Mn1/3Co 1/3O 2 from lithium ion battery recovery stream. J Power Sources 2015;282:140–5. https://doi.org/10.1016/j.jpowsour.2015.02.046.
[179] Zhao Y, Yuan X, Jiang L, Wen J, Wang H, Guan R, Zhang J, Zeng G. Regeneration and reutilization of cathode materials from spent lithium-ion batteries. Chem Eng J 2020;383:123089. https://doi.org/10.1016/j.cej.2019.123089.
[180] Argonne National Laboratory. Lithium-ion battery recycling R&D center: recell. 2019. https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell/. [Accessed 9 January 2023].
[181] Neumann J, Petranikova M, Meeus M, Gamarra JD, Younesi R, Winter M, Nowak S. Recycling of lithium-ion batteries-Current state of the art, circular economy, and next generation recycling. Adv Energy Mater 2022;12(1):1–26. https://doi.org/10.1002/aenm.202102917.
[182] Émbil MI, Valero A, Ortego A, Villacampa M, Vilaró J. Raw material use in a battery electric car – a thermodynamic rarity assessment. Resour Conserv Recycl 2020;158:104820. https://doi.org/10.1016/j.resconrec.2020.104820.
[183] Korhonen J, Honkasalo A, Seppälä J. Circular economy: the concept and its limitations. Ecol Econ 2018;143:37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.

[184] Reuter M, Schaik AV. Sustainability made in delft. In: Mulder KF, editor. Fundamental limits and challenges of recycling. E-Publishing Inc., Delft University of Technology; 2006. p. 51–61. https://www.researchgate.net/publication/277325321_Fundamental_limits_and_challenges_of_recycling.
[185] Liu Z, Liu G, Cheng L, Gu J, Yuan H, Chen Y, Wu Y. Development of sustainable and efficient recycling technology for spent Li-ion batteries: traditional and transformation go hand in hand. Green Energy Environ 2023. https://doi.org/10.1016/j.gee.2023.09.001.
[186] O'Neill S. Battery recycling challenge looms as electric vehicle business booms. Engineering 2021;7:1657–60. https://doi.org/10.1016/j.eng.2021.11.009.
[187] Sultana I, Chen Y, Huang S, Rahman MM. Recycled value-added circular energy materials for new battery application: recycling strategies, challenges, and sustainability-a comprehensive review. J Environ Chem Eng 2022;10:108728. https://doi.org/10.1016/j.jece.2022.108728.
[188] Swedish Energy Agency. State-of-the-art in reuse and recycling of lithium-ion batteries- A research review. 2019. http://www.energimyndigheten.se/globalassets/forskning–innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf.
[189] Sommerville R, Zhu P, Rajaeifar MA, Heidrich O, Goodship V, Kendrick E. A qualitative assessment of lithium ion battery recycling processes. Resour Conserv Recycl 2021;165:105219. https://doi.org/10.1016/j.resconrec.2020.105219.
[190] Sommerville R, Stewart JS, Goodship V, Rowson N, Kendrick E. A review of physical processes used in the safe recycling of lithium ion batteries. SMT Trends 2020;25:1–11. https://doi.org/10.1016/j.susmat.2020.e00197.
[191] European Commission. Batteries Europe. European technology and innovation platform (ETIP) WG2: raw materials and recycling roadmap. 2021. https://ec.europa.eu/energy/content/batteries-europe-raw-materials-and-recycling-roadmap_en.
[192] Lander L, Tagnon C, Nguyen-Tien V, Kendrick E, Elliott RJR, Abbott AP, Edge JS, Offer GJ. Breaking it down: a techno-economic assessment of the impact of battery pack design on disassembly costs. Appl Energy 2023;331:120437. https://doi.org/10.1016/j.apenergy.2022.120437.
[193] U.S. Department. Of energy. 2023. https://www.energy.gov/articles/biden-harris-administration-announces-192-million-advance-battery-recycling-technology. [Accessed 17 October 2023].
[194] Global Battery Alliance. Battery passport pilot. 2023. https://www.globalbattery.org/action-platforms-menu/pilot-test/. [Accessed 2 October 2023].
[195] Noerochim L, Suwarno S, Idris NH, Dipojono HK. Recent development of nickel-rich and cobalt-free cathode materials for lithium-ion batteries. Batteries 2021;7(4):84. https://doi.org/10.3390/batteries7040084.
[196] Benchmark Mineral Intelligence. Nickel V Cobalt: the secret EV battle for the lithium ion battery. 2018. https://www.benchmarkminerals.com/nickel-v-cobalt-the-secret-ev-battle-for-the-lithium-ion-battery/. [Accessed 9 January 2023].
[197] Hague Center for Strategic Studies. Graphite: supply chain challenges and recommendations for a critical mineral. 2022. https://hcss.nl/report/graphite-supply-chain-challenges-recommendations-for-a-critical-mineral/.
[198] Talga Group Ltd. Advanced progress with European investment bank for Vittangi anode project funding. ASX release; 2022. https://talgagroup.eu-central-1.linodeobjects.com.
[199] Leading Edge Materials Corp. Leading edge materials provides update on Woxna graphite project. News release; 2018. https://leadingedgematerials.com/wp-content/uploads/2018/07/2018-07-05_NR_LME.
[200] Yu TQZ, Xie W, He Y, Wang H, Zhang T. Preparation of onion-like synthetic graphite with a hierarchical pore structure from anthracite and its electrochemical properties as the anode material of lithium-ion batteries. Energy Fuels 2022;36:8256–66. https://doi.org/10.1021/acs.energyfuels.2c01892.
[201] Shi M, Song C, Tai Z, Zou K, Duan Y, Dai X, Sun J, Chen Y, Liu Y. Coal-derived synthetic graphite with high specific capacity and excellent cyclic stability as anode material for lithium-ion batteries. Fuel 2021;292:120250. https://doi.org/10.1016/j.fuel.2021.120250.
[202] Xing B, Zhang C, Cao Y, Huang G, Liu Q, Zhang C, Chen Z, Yi G, Chen L, Yu J. Preparation of synthetic graphite from bituminous coal as anode materials for high performance lithium-ion batteries. Fuel Process Technol 2018;172:162–71. https://doi.org/10.1016/j.fuproc.2017.12.018.
[203] Bitew Z, Tesemma M, Beyene Y, Amare M. Nono-structured silicon and silicon based composites as anode materials for lithium ion batteries: recent progress and perspective. Sustain Energy Fuels 2022;6:1014–50. https://doi.org/10.1039/D1SE01494C. Royal Society of Chemistry.
[204] Guo Z, Qian G, Wang C, Zhang G, Yin R, Liu WD, Liu R. Progress in electrode materials for the industrialization of sodium-ion batteries. Prog Nat Sci 2022 December:1–7. https://doi.org/10.1016/j.pnsc.2022.12.003.
[205] Grandi TD. 4 benefits of LFP batteries for EVs. 2023. https://www.visualcapitalist.com/sp/4-benefits-of-lfp-batteries/#:~:text=Today%2C%20these%20batteries%20are%20becoming%20increasingly%20popular%20in,2022%2C%20according%20to%20the%20International%20Energy%20Agency%20%28IEA%29. [Accessed 2 October 2023].
[206] Ballinger B, Stringera M, Lopeza DRS, Kefford B, Parkinson B, Greig C, Smart S. The vulnerability of electric vehicle deployment to critical mineral supply. Appl Energy 2019;255:113844. https://doi.org/10.1016/j.apenergy.2019.113844.
[207] Sim K, Eom KS. Nanoplates-stacked vanadium oxide cathode employing higher kinetics and stability in a lithium-ion battery. Meet Abstr 2022:2254. https://doi.org/10.1149/MA2022-01552254mtgabs.
[208] Bhosale AP, Bodke K, Babhulkar A, Amale S, Mastud SA, Chavan AB. Comparative environmental assessment of different battery technologies used for electric vehicles. Mater Today: Proc 2022;72(3):1446–56. https://doi.org/10.1016/j.matpr.2022.09.344.
[209] Nylund PA, Brem A, Agarwal N. Enabling technologies mitigating climate change: the role of dominant designs in environmental innovation ecosystems. Technovation 2022;117:102271. https://doi.org/10.1016/j.technovation.2021.102271.
[210] Brem A, Díaz RP. Are you acting sustainably in your daily practice? Introduction of the Four-S model of sustainability. Clean. Prod 2020;267:122074. https://doi.org/10.1016/j.jclepro.2020.122074.
[211] Wang C, Cong J, Wang K, Qi Y, Cai W, Li Y, Fu S, Wang W, Wei Y, Zheng X, Jiang J, Chen M, Liu W, Zhang Y, Tian Z, Chen J, Li R, Zu H. Research on China's technology lists for addressing climate change. CJPRE 2021;19:35–45. https://doi.org/10.1016/j.cjpre.2021.12.017.
[212] Seo N. The behavioral economics of climate change: adaptation behaviors, global public goods, breakthrough technologies, and policy-making. Muaebak Institute of Global Warming Studies, Seoul, Korea. In: Chapter 5: breakthrough technologies: technological innovations as an alternative global warming solution. Bangkok, Thailand: Chulalongkorn University; 2017. p. 139–83. https://doi.org/10.1016/B978-0-12-811874-0.00005-2. E-Publishing Inc.
[213] Mali B, Shrestha A, Chapagain A, Bishwokarma R, Kumar P, Longatt FG. Challenges in the penetration of electric vehicles in developing countries with a focus on Nepal. Renew. Energy Focus 2022;40:1–12. https://doi.org/10.1016/j.ref.2021.11.003.
[214] Murugan M, Marisamynathan S. Analysis of barriers to adopt electric vehicles in India using fuzzy DEMATEL and Relative importance Index approaches. Case Stud. Transp. Policy 2022;10:795–810. https://doi.org/10.1016/j.cstp.2022.02.007.
[215] Franzo S, Nasca A. The environmental impact of electric vehicles: a novel life cycle-based evaluation framework and its applications to multi-country scenarios. J Clean Prod 2021;315:128005. https://doi.org/10.1016/j.jclepro.2021.128005.
[216] McGlade C, Ekins P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature 2015;517:187–90. https://doi.org/10.1038/nature14016.
[217] IEA (International Energy Agency). World energy investment 2021. 2021. https://iea.blob.core.windows.net/assets/5e6b3821.
[218] Asselt HV. Governing fossil fuel production in the age of climate disruption: towards an international law of 'leaving it in the ground'. Earth System Governance 2021;9:100118. https://doi.org/10.1016/j.esg.2021.100118.