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Sustainability of the use of critical raw materials in electric vehicle batteries: A transdisciplinary review

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ABSTRACT

The expected growth of electric mobility will have major sustainability implications in societies across the globe due to a global reliance on primary natural resources and the uneven distribution of benefits and impacts. There has been a call for comprehensive assessments that account for the complex causalities between technological, environmental, social, economic, and political aspects of electric mobility. We present a literature review examining the interconnections between aspects of sustainability in the use of critical materials in electric vehicle batteries. With a holistic review of social sciences, materials science, environmental policy, and innovation management literatures, five domains of sustainability tensions were identified: 1) resource sufficiency, 2) geographical distribution and global value chains, 3) regulation and policies, 4) circular economy, and 5) emerging battery technologies. The framework explicates the wickedness and complex causalities involved in the interdependencies of multiple sustainability dimensions and the related tensions. This study extends the examination to cover political aspects and adds to techno-industrial research on battery materials, supply chains and industrial policies and land use, electricity consumption and governance in EV battery production. This study proposes pathways forward that consider various sustainability interdependencies.

1. Introduction

Electric mobility is a crucial part of the green transition (David and Koch, 2019). Electric vehicles (EVs) are considered vital in meeting the global climate goals of the transportation sector (Alanazi, 2023), which currently accounts for more than a third of CO2 emissions from end-use sectors (IEA, 2023b). To reach the climate goals, the International Energy Agency (IEA) has forecasted that the global EV stock will need to grow by 36 % a year, reaching altogether 230 million vehicles by 2030 (IEA, 2021, IEA, 2023a; Gabbatish, 2021). Such a growth rate would be revolutionary, carrying major environmental, economic, social, and political implications. Hence, there is a call for a systemic review to develop understanding of the sustainability risks related to battery materials at the regional and global levels (Jannesar Niri et al., 2024; Huber and Steininger, 2022).

This paper answers to the call by addressing the dilemma of global reliance on primary natural resources of electrification of mobility and to account for the complex causalities between technological, environmental, social, economic, and political aspects of electric mobility. A holistic transdisciplinary understanding about the sustainability of the use of raw materials in EV batteries is needed for several reasons: the battery production relies heavily on the primary resources (Jürgens et al., 2021; Newman et al., 2014), causes various (often adverse) environmental and social impacts locally, and challenges social acceptance and sustainability governance of the sector (Mononen et al., 2022; Tiainen et al., 2015). Our research question is: How are the different aspects of sustainability of the use of critical materials in electric vehicle batteries interconnected and what are the implications for electric mobility?

The production of EV batteries is dependent on critical raw materials (CRMs). CRMs refer to metals and other resources that exhibit a significant economic importance to a country or market area, simultaneously

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to a supply risk. CRMs include cobalt, lithium, natural graphite, and rare earth elements (REEs), needed for the electrification of mobility. Some countries or regions, such as the EU, also distinguish strategic raw materials (SRMs) that consist of CRMs and additional materials, which are essential for reaching the climate targets and are expected to be in high demand in the future. SRMs in the EU include for example copper and nickel, which are important for its green, digital, space and defence applications, including EVs. Countries publish and regularly update lists of CRMs and SRMs depending on what is seen critical in each country at different times (Sandell-Hay, 2021; Su and Hu, 2022).

In this paper, we present a transdisciplinary integrative literature review (Elsbach and Knippenberg, 2020; Post et al., 2020; Stinder et al., 2022) of CRMs for EV batteries. To build a holistic view on the complex causalities, we incorporate knowledge from multiple branches of natural and social sciences, including sub fields of materials science, environmental policy, and innovation management. The review was conducted in four steps. First, we mapped the key challenges related to the sustainability of electric mobility. We adopted the concept of *wicked problem* (Endl, 2017) to direct attention to a wide nexus between climate, energy, mobility, metallic raw materials, and mining in examining EV battery metals. Second, we identified five central sustainability challenges, called *domains of tension,* associated with CRMs that have received less attention from a holistic perspective in the literature: 1) resource sufficiency; 2) geographical distribution and global value chains; 3) regulation and policies; 4) circular economy; and 4) implications of emerging battery technologies. These five dimensions were selected based on the transdisciplinary literature review because they address the extraction, distribution, and use of CRMs and the competing innovations and technologies for CRMs in EV batteries. Third, we analyzed the interwoven dependencies and systemic complexities. Finally, we developed a framework for assessing the sustainability tensions in the use of CRMs and highlighted potential sustainability pathways forward.

The novelty of this paper is that it explicates the complexities involved in the interdependencies of multiple sustainability dimensions and the identified domains of tension. This study complements the state-of-the-art by addressing the topics of resource sufficiency, geographical distribution of raw materials and global value chains, regulation and policies, circular economy, and emerging battery technologies. We aim to pave the way for an environmentally and socially sustainable future for EV battery solutions. This study adds to techno-industrial research on battery materials, supply chains and industrial policies (Barman et al., 2023) and land use, electricity consumption and governance in EV battery production (Jannesar Niri et al., 2024; Sanches-Lopez, 2023) by highlighting the hidden causalities between the multiple sustainability dimensions involved in the use of critical materials in EV batteries and proposing pathways forward.

The paper is structured as follows. First, we introduce the wicked problem approach for the analysis of sustainability of the use of critical raw materials for the EV batteries. Second, we describe the methodology used in this study. Third, we present a review of the five sustainability challenges of critical materials for the EVs and their batteries. Fourth, we summarize the analysis of the sustainability tensions in connection to each challenge, including a discussion about the complexities involved. Finally, we present the conclusions together with an outline for future research.

2. Wicked problem as an approach for analyzing sustainability of critical materials for electric vehicle batteries

Phrase *wicked problem* was originally introduced in the 1970s' in social policy by Horst Rittel and Webber (1973) to describe a problem that is difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often challenging to recognize. The phenomenon was contrasted with *a tame problem* that can be solved with the existing modes of inquiry and decision-making. The term 'wicked' was used, not in the sense of evil, but rather as resistance to clear or unambiguous resolution. Due to the inherent complex interdependencies of various aspects of wicked problems, the effort to solve one aspect of a wicked problem may reveal or create other problems. Thus, a wicked problem is a complex challenge that defies a complete definition and lacks a straightforward solution. Instead, all possible solutions are neither true or false, nor good or bad, but somewhere in-between and the best that can be done at the time (Conklin, 2005; Head, 2019). Wickedness is a characteristic of the problem/solution space and the cognitive dynamics of exploring that space and offers possibility to understand and frame the complex phenomena (cf. Conklin, 2005).

The concept of wicked problem has been used to analyze global environmental and resource sufficiency issues and planetary dilemmas (Brown et al., 2010; Head, 2019; Hull et al., 2020). The EV critical raw materials challenge is such a dilemma (Endl, 2017). Various dimensions of global sustainability and resource management topics interact in ways that are so complex and intertwined that our knowledge of the problem will always be only partial, fallible, and uncertain.

Therefore, Jacqueline Russel (Russel, 2010, 55) suggested that we need "an approach to inquiry and decision-making that remains flexible and open to revision and improvement." Brown et al. (2010, 4) have argued: "Since wicked problems are part of the society that generates them, any resolution brings with it a call for changes in that society. This leads to an idea that wicked problems must be understood in some societal and practical context. Jeff Conklin (2005) noted that we can better understand the features and dynamics of wicked problems when integrating them into the concepts of social and technical complexities. Social complexity refers to the number and diversity of actors who are involved. Technical complexity includes the number of technologies that are involved in the issues, the immense number of possible interactions among them, and the content and consequences of possible technical change.

Fig. 1 shows the complex interdependencies of various aspects of EV raw materials making it a wicked problem. Fig. 1 illustrates how the dimensions of sustainability are connected to several thematic areas of EV battery sustainability. On top of the figure, the three key sustainability pillars, environmental, social and economic (Elkington, 1997), are cross-cutting in that they are all linked with all domains of tension presented at the bottom of the figure. In consequence, the figure shows that none of the domains of tension can be addressed without affecting the others. Additionally, addressing an individual sustainability dimension (environmental, social, economic) with only one theme is difficult without consequences for the other dimensions. This means that also the three sustainability dimensions are inherently linked. Besides being highly complex in definition, it is evident that the EV critical raw material challenge is something that crosscuts multiple levels, from global to regional, and involves numerous stakeholders, often with conflicting interests or values (see Alford and Head, 2017).

Fig. 1 reveals that sustainability of the use of critical raw materials in EV batteries is a wicked problem. As an example, environmental sustainability relates to the environmental impacts by mapping, mining, extraction and circularity of battery raw materials. These, in turn, are related to all five domains of tension: resource sufficiency (utilization of finite reserves), geographical distribution and global value chains (nature of the deposits, their accessibility and quality, hence technologies and value chains that will process the raw materials towards EV batteries and bring them into selected markets), regulation and policies (mining laws, environmental laws and acts), circular economy (utilization of secondary raw materials, collection, sorting and transport of secondary streams, processing technologies and value chains) and emerging battery technologies (alternative chemistries and value chains, challenging of established technologies for circular economy). As demonstrated via the examples, all the five domains of tension are also interlinked, and they have the dimensions of social sustainability (jobs, impacts on local communities, distribution of gains and harms)

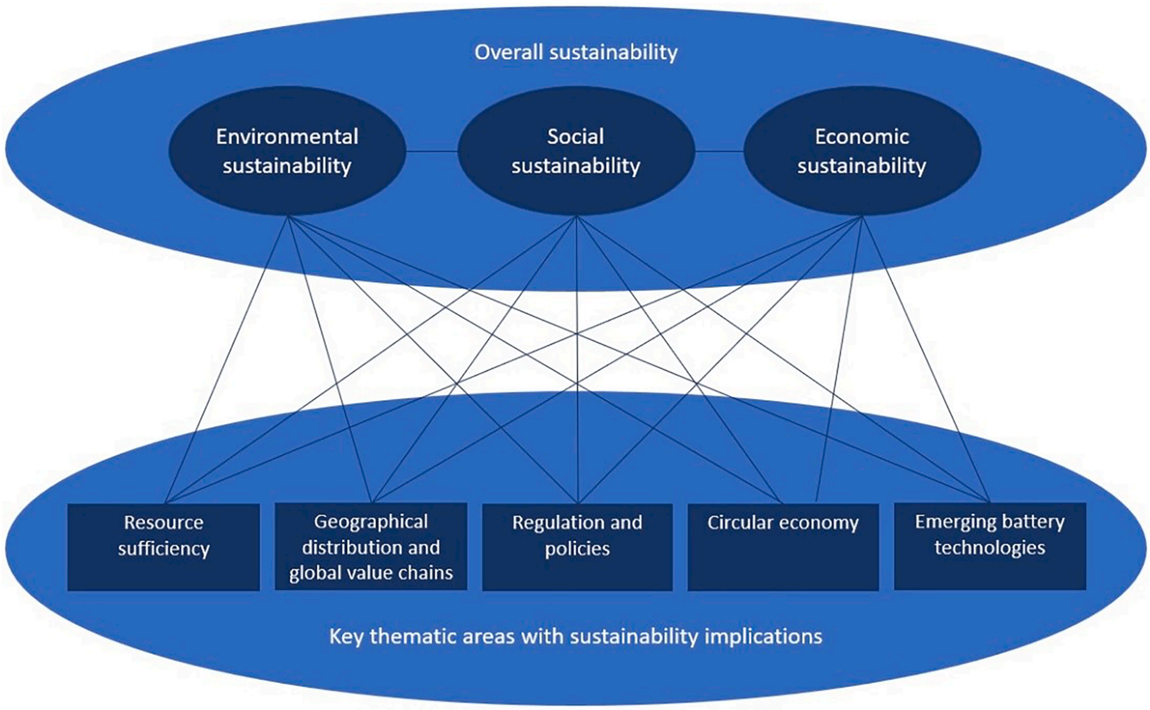

Fig. 1. Interdependences between sustainability and thematic areas of critical raw materials in EV batteries.

and economic sustainability (ownership, added value, business models).

3. Methodology

A transdisciplinary integrative literature review (Elsbach and Knippenberg, 2020; Post et al., 2020) was conducted to create a holistic understanding about the sustainability of the use of critical raw materials in EV batteries. First, we identified discipline-specific reviews of academic research, policies, and strategies on the topic. Each researcher reviewed literature in their disciplinary domains and wrote descriptive analysis of the body of literature. We then compared the reviews in each body of literature to scrutinize the intersections of different discipline-based understandings. The multi-disciplinary group of authors systematically discussed the identified themes (five domains of tension) related to the use of CRMs in EVs (Fig. 1). The integrated review was first merged into a shared overview of the themes, and then further analyzed regarding potential tensions within each domain. Finally, the sustainability framework (Elkington, 1997) was adopted to systematically analyze each sustainability dimension and to account for the complexities involved in the use of critical raw materials. This resulted in the identification of possibilities proposing pathways forwards that consider all facets of the socio-technical change in the study of sustainable use of critical raw materials for EVs.

This method of literature review has two rationales. First, a multidisciplinary literature review helps to understand the variety of aspects that contribute to the complexity of sustainable use of critical raw materials. A multidisciplinary literature review connects established but previously unconnected perspectives, allowing for the integration of research findings from disparate sources in an original way and resulting in the emergence of new perspectives (Post et al., 2020). Second, a relatively comprehensive review of literature on the use of CRM in EVs reveals what is interesting and useful in advancing research on the sustainable use of critical raw materials (Elsbach and Knippenberg, 2020). A typical error in this kind of study is that the scope of the review is either too narrow or too broad. To ensure that we had a relevant scope of studies on the emerging issue of sustainability of CRM in EVs, we included the most recent literature in our review and took stock of literature that examined the availability and governance of CRM and alternative technologies and materials for CRM. This allowed us to identify the nature of sustainability complexities that actually arise and to present value-added insights for future theory development and research agenda on sustainability of electric mobility.

The scope of the work is on critical raw materials to the EU (despite other possible CRM definitions), therefore the European perspective prevails. This is correlated with a European viewpoint to societal structures, like governmental, legal and education systems, and economy of free markets. Citizens are considered as members of a democratic society with defined human rights, such as the right to vote, and freedom of speech.

4. Domains of tension

The green transition requires radical technological changes across all areas of society, including the entire energy system, industry, and transportation. In consequence, the systemic change will require new investments, and therefore, significantly increase the demand for many raw materials (Valero et al., 2018). The production of EVs, and particularly their batteries, consumes significantly more CRMs and strategic raw materials (SRMs), such as lithium, cobalt, copper, nickel, and graphite (Lipman and Maier, 2021; IEA 2023a), in comparison to conventional internal combustion engine vehicles (ICEVs). In the EU, CRM refers to raw materials that are of high economic importance but exhibit a clear supply risk. The first list of CRMs by the EU was released in 2011, which was updated for the fifth time in 2023 (European Commission, 2023). The term SRM was recently introduced in the EU Critical Raw Materials Act to highlight raw materials that are strategically important to the green transition in EU and are expected to see significant growth in future demand. Therefore, many of the SRMs are employed also in other green technology areas, such as energy production. For example, wind turbines require CRMs and SRMs, like rare earth elements (REEs, e.g., neodymium, dysprosium, and praseodymium), which are also essential for the EV motors (Garcia-Olivares et al., 2021; Valero et al., 2018).

The anticipated growth in raw material demand in electric mobility will exert immense pressure to accelerate ore exploration and extraction activities. The foreseen increase in metals production will raise the question about the sufficiency of global mineral resources (Gregoir et al., 2022; Michaux, 2022). For many metals, e.g., nickel, lithium, and cobalt, the reserves may not be able to respond to the demand (Earl et al., 2022; Michaux, 2022). Copper demand is forecasted to exceed the projected copper mineral resources by mid-century, 2050, (Elshkaki et al., 2016; Seck et al., 2020) and the uncertainties about the future supply-demand balance have been clearly stated for materials, such as lithium (Hache et al., 2019). This requires targeting lower-grade mineral deposits and more difficult-to-reach locations with larger environmental footprint and higher economic costs (Jannesar Niri et al., 2024). Moreover, the extraction of CRMs includes the risks of geopolitical tensions, human rights violations, bribery and corruption, armed conflicts, environmental emissions, water stress, loss of biodiversity, environmental justice and community risks (Bamana et al., 2021; Church and Crawford, 2018; Lèbre et al., 2020; Owen et al., 2022; Rachidi et al., 2021). For example, more than two thirds (69 %) of energy transition mineral projects (5097 projects) are located on Indigenous and Peasant lands, and 62 % of those with adverse conditions for permitting, consultation, and consent processes (Owen et al., 2022).

The increase in demand of critical raw materials, the political, social and economic tensions and the environmental issues have been recognized in the different bodies of literature. However, a holistic review of these aspects in the extraction, distribution, and use of CRMs and the competing innovations and technologies for CRMs in EV batteries are few. In the following, we will examine the five *domains of tensions* associated with critical raw materials, namely: 1) resource sufficiency; 2) geographical distribution and global value chains; 3) regulation and policies; 4) circular economy; and 5) implications of emerging battery technologies, in detail.

4.1. Resource sufficiency

The forecasted increase in demand for materials to meet the carbon-neutrality targets in the transportation sector is so dramatic that it is not possible to increase the production capacity quickly enough to ensure adequate supply. Many of the low-carbon solutions are considerably more metal-intensive than conventional counterparts (Kleijn et al., 2011; Valero et al., 2018). As shown in Fig. 2, EVs require significantly more materials than ICEVs, such as lithium (batteries), copper (cabling), nickel (batteries), manganese (batteries), cobalt (batteries), graphite (batteries) and REEs (permanent magnets in EV motors), which are also in increasing demand for many power generation technologies. Significantly, all these materials have been included in the most recent list of CRMs (Carrara et al., 2023).

Resource sufficiency predictions for different scenarios at desired intervals, based on the projections of the increase in the demand for battery metals until 2060, raise concerns for pushing the planetary boundaries (Fig. 3). Although the demand for copper and nickel (in mass) will increase radically (Elshkaki et al., 2016), that for cobalt and lithium will grow even more significantly in relation to current production (Seck et al., 2022). In theory, the global reserves for many of the minerals are likely to be sufficient for meeting the future demand, but the questions about quality and access to the reserves are also important (Granvik, 2021). Low-grade reserves are often difficult to reach, which increases the costs for mining and processing, and may require new technology for efficient exploitation. The shift to low-grade deposits also adds to the local environmental burden through rising water use that increases competition with other water users and adds greater

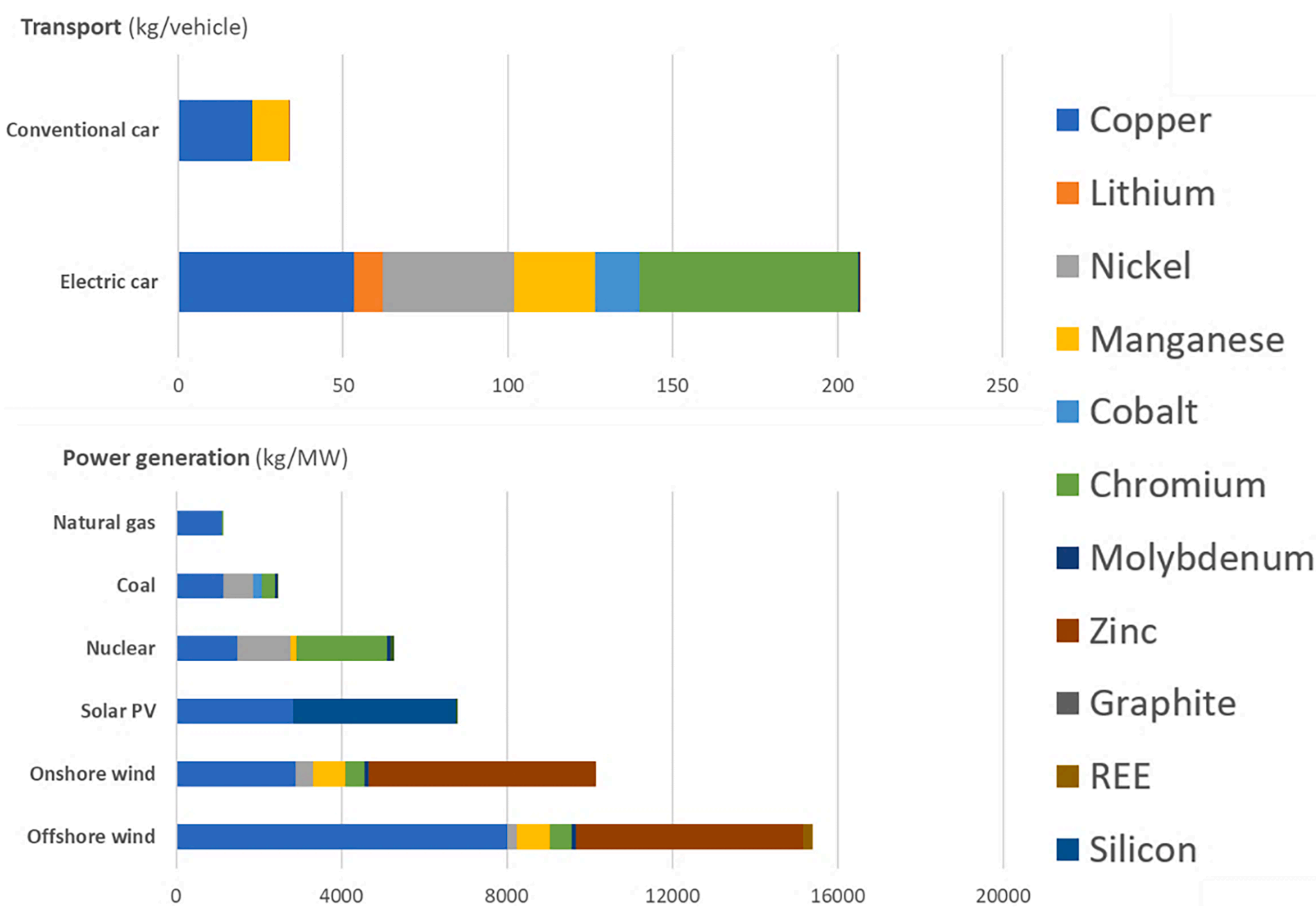

Fig. 2. The demand for metals in transport and power generation (IEA, 2020; IEA 2023a).

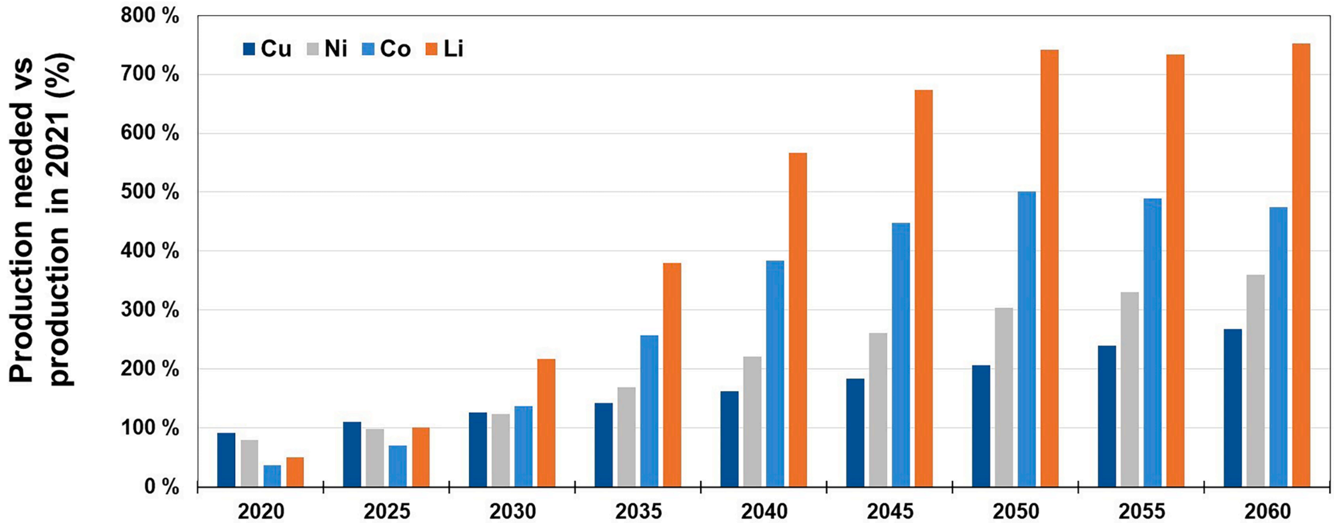

Fig. 3. Projection of the increase in demand for battery metals between 2020 and 2060 at five-year intervals (with linear dependencies). The total demand in 2020 covers the shares of transport and energy production plus other demand (Granvik (2021).

contribution by side streams, like mining tailings, and potential emissions (e.g., Jannesar Niri et al., 2024). Additionally, the capacity of existing mines becomes a bottleneck for primary production, given that establishing new sites takes typically 5 – 25 years from the discovery of a promising ore deposit, depending on the regulatory processes and preliminary assessments. Eventually, there may come a situation where there are the enabling technologies for virtually zero-emission environmentally sustainable mining and production of battery metals, but the market does not bear the additional costs required for the necessary investments.

To understand the environmental impacts of demand increase for CRMs, it is important to consider all phases of the life cycle, from raw material extraction to the end-of life. The primary production, i.e., mining and extraction, of metals is often (fossil) energy- and water-intensive, which means the indirect environmental impacts of electrifying mobility can be manifold compared to the direct impacts (e.g., Golroudbary et al., 2022; Lai et al., 2022). Therefore, the used energy mix plays a key role in the magnitude of greenhouse gas (GHG) emissions released by the primary production (Shafique and Luo, 2022), and the used energy mix varies significantly between countries and even between individual stakeholders. However, the shift towards renewable energy technologies, particularly wind, is based on the use of the same CRMs as EVs and their batteries: copper, nickel and REEs (Fig. 2). Therefore, renewable energy production further intensifies the demand for metals, which, in turn, necessitates more renewable energy, creating a self-sustaining loop in which the global metal production capacity is insufficient to supply the growing markets. The loop is likely to result in the depletion of some CRMs within as short time frame as 5 to 10 years. For example, the supply and the foreseen increase in the demand of REEs is clearly imbalanced (e.g., Habib and Wenzel, 2014).

Another aspect of environmental impacts is that the production of EVs currently releases more GHGs than the production of ICEVs. Recently, Volvo (2021) published a report presenting the carbon footprint of their fully electric car model compared to a corresponding model powered by an internal combustion engine. According to the results, the accumulated GHG emissions by manufacturing of an electric car were almost 70 % higher than those of a combustion engine model. The break-even point between the two vehicle types was reported to occur between 49,000 and 110,000 km, depending on the electricity mix used. This means that GHG emissions from EVs are lower only after this critical distance during the use phase is passed.

The battery production chain is complex and can be organized in many ways. Mining and refining activities of battery metals often occur in separate locations, and the refining process of a single metal can involve several steps. The geographical location of the production sites plays a key role in the resulting carbon footprint due to varying energy mixes (Melin et al., 2019). The processing of raw materials into precursory and active battery materials as well as the manufacturing of battery cells requires plenty of energy, resulting in GHG emissions (Hill et al., 2019; Lai et al., 2022). For example, in Sweden, the energy mix consisting of high share of renewable and nuclear energy causes less GHG emissions that the typical mixes in China or Poland, which rely largely on coal (Shafique and Luo, 2022). Furthermore, primary production may release masses of side streams, so their banking may occupy the land nearby.

In summary, previous research has shown that due to electrification of society, the demand for raw materials exceeds planetary boundaries. The increased demand causes an increase in prices of raw materials, but also, attracts investments. EV battery production is energy-intensive and requires clean energy solutions to reduce the dependency on fossil fuels. Maintaining resource sufficiency requires opening new mines, and both the old and new mines have significant local social and environmental impacts.

4.2. Geographical distribution and global value chains

The global value chains of CRM influence strategic relations and economic opportunities among individual businesses, industry sectors and nations. The location of the desired ore deposits determines where their extraction must also take place. However, the distribution of these deposits is unevenly divided between countries and regions, creating a basis for geopolitical and trade tensions as the supply of metals becomes a limiting factor for key technologies (Sandell-Hay, 2021; Su and Hu, 2022). Ensuring reliable and secure access to critical raw materials, particularly critical battery materials, is a growing concern worldwide.

The reserves and production of cobalt, lithium and graphite are concentrated among a relatively small number of countries, which gives them a special role in the global value chains. The Democratic Republic of Congo (DRC) possesses approximately one third of the known global cobalt reserves and accounts for almost 60 % of the cobalt production – often under the control of Chinese ownership or long-term agreements with Chinese partners (Rachidi et al., 2021; Ericsson et al., 2020). According to the U.S. Geological Survey (2022), the largest lithium reserves in the World are in South America: Bolivia 21 million tons; Argentina 19 million tons; and Chile, 9.8 million tons. Despite having the fourth largest reserves, Australia is clearly the leading lithium producer, doubling Chile's production numbers, which is in second place (EC 2020b). For natural graphite, China dominates both the reserves and the production by the share of over 80 % (Ibid).

Most of the global cobalt refining is carried out in China, although the extraction is conducted largely in the DRC. In comparison, the second largest producer of refined cobalt, Finland, has approximately only 1 % of global cobalt reserves (EC, 2018). Overall, the contribution by China to battery production up to date is incomparable along the entire value chain (Tracy, 2022). The situation may change in the future, as battery factories are rapidly being established around the world. However, the strong position of China in the raw materials ownership and processing is likely maintained due to the strategy of protecting intellectual property rights of key technologies, like battery technologies. Hence, China secures the access to raw materials by governance and/or high price but also by limiting the access of possible competitors to the necessary technologies (Naumanen et al., 2019).

The dependence on China has become an issue both in Europe and the US (van Wieringen and Fernández Álvarez, 2022), particularly concerning the recent geopolitical developments (e.g., war in Ukraine). The risks associated with the centralized production are in many cases compounded by low substitution and recycling rates of the materials. By publishing the list of CRMs, EU aims to strengthen the competitiveness of the European industry and stimulate the production of CRMs with more mining and circular economy activities domestically (EC, 2020). The EU's technological dependence on resources exported from resource-abundant countries has driven the EU to take an active role in the raw material realm – a topic that has been in policy agendas since the first list of CRMs in 2011 (EC, 2011). Recently, the agenda has expanded to encompass other issues, such as the sustainability of the CRMs value chains and resource governance (EC, 2023).

There are some known CRM reserves in Europe. Reserves of cobalt have been discovered in Finland, Sweden, Spain, Greece, and Poland, but it is currently derived only in Finland as a by-product of nickel or copper extraction (Fig. 4). The EU does not have any active lithium mines (except one run by Grupo Mota, in the Guarda region of Portugal, which output goes exclusively to the ceramics industry), but there are several ongoing mine development projects in Austria, Czech, Finland, Germany, Portugal, Spain, and Serbia. In 2022, Sibanye-Stillwater (the majority owner of Keliber project, Finland) made an investment decision to start the operation of first European lithium mine and lithium chemical production for batteries in Finland. Natural graphite is mined in Austria, Germany, Romania and Sweden, accounting only to 0.2 % of the global output. However, the most important known natural graphite deposits within EU are in Sweden and Finland, where also new projects are being developed. Despite the known reserves of the above materials in the EU, many development projects face significant social risks and face local opposition, which may hinder or prevent their realization (Mononen et al., 2022; Kivinen et al., 2020).

A global perspective on value chains of CRMs directs attention to how and why sustainability transitions are similar or different across locations. Asian countries (chronologically first Japan, followed by South Korea and China) have long been business drivers in the battery value chain, especially in the manufacturing of battery chemicals and cells. For the EU, the discrepancy between the remote origin of battery materials and its strong position (second largest) in global electric car production poses a challenge (EC, 2020b). Given that the EU contributes only to 3 % of global production of lithium-ion batteries, the dependence on the earlier steps in value chain is evident. This means an unfavorable distribution of economic gains along the added value in the products, and GHG emissions caused by the bad energy mix in processing and transportation of materials. However, the position of European players in the battery value chain has strengthened significantly over the past few years. For example, the first European lithium mine and chemical plant to produce raw material for the battery industry are expected to be opened in Finland 2025–2026. Other investment examples include the ongoing construction of BASF battery material (precursor) plant in Harjavalta (Finland), the cathode active material plant of Umicore in Nysa (Poland) and the already-opened battery recycling plant of Northvolt (Revolt) in Skellefteå (Sweden). Further up in the value chain, several new battery factories are under construction or planning in Europe (Companies invest in EV battery factories in Europe|Reuters). Tesla opened a gigafactory in Berlin (Germany) in 2022 and Volkswagen has announced plans for six factories in the EU. In battery recycling, Stena Recycling has announced an investment for a new facility in Halmstad (Sweden).

Watari et al. (2021) have addressed that, in the case of metals for electric mobility, one third or even more of the increase in resource extraction is expected to occur in countries with weak and failing resource governance. This comes at the cost of severe local environmental degradation and unequal distribution of economic benefits within impacted communities. The sustainability argument directs attention to *where* the resources exist and are processed, *who* collects majority of the value in the production chain, and *what* actions might eventually support more equal welfare distribution. As shown in Fig. 4,

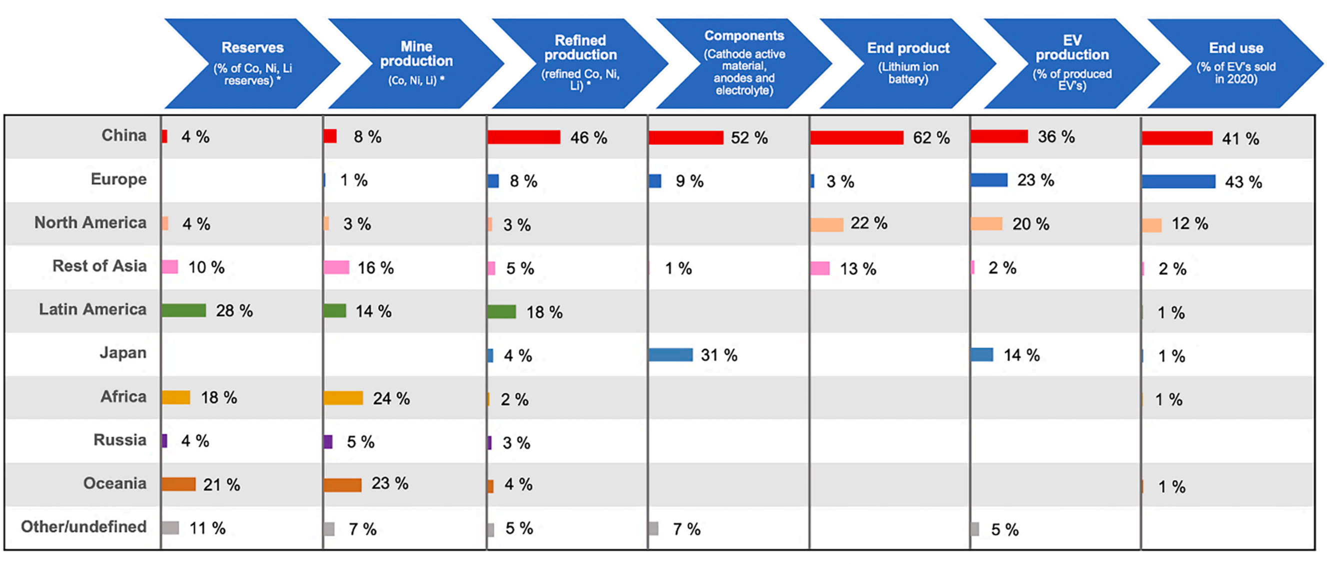

Fig. 4. Lithium-ion battery metals in different countries (Granvik, 2021).

the value chains are strongly polarized into the initial phases that occur in developing countries and value-adding refining and end-use phases that take place in developed countries. Latin America, Oceania and Africa account for most of the extraction, whereas China, Japan, Europe and USA are the key players in value-adding steps of the battery value chain. Ultimately, the end use concentrates in China, Europe and North America.

A circular economy will modify the future raw material value chains and may open new possibilities to dilute the polarization of the value chains via lowering the pressure for primary raw materials extraction. The role of secondary raw materials in the battery value chain will increase with the increase in demand for CRMs especially in regions with high EV population, such as the EU, China, and North America. Bongarts et al. (2021) have highlighted the importance of urgent actions towards developing effective recycling processes for many key battery minerals and copper and Silvestri et al. (2021) have indicated similar concerns regarding the recycling technologies for REEs. In turn, the added value may remain and further accumulate in the countries with advanced technologies.

In summary, the global value chains of CRM have a large carbon footprint of logistics due to the discrepancy between geographical locations of mining, mineral production, and car manufacturing.

The global value chains have an unequal distribution of wealth in countries participating in the value chain. The inequality between the global North and global South is likely to continue as the technological competition in electrification of mobility in the global North increases the demand for CRMs. Simultaneously, the diffusion of electric mobility innovations in the global South is slow.

4.3. Regulation and policies for raw materials for electric mobility

The policy needs and regulatory options for the CRM value chains are many. Laws, regulations, policy instruments, information guidance, voluntary agreements, financial incentives, and taxation instruments are among the options to govern the sustainability of the use of CRMs in EVs. However, there is variance in implementation of policies and regulations among the large market players, China, Europe, and North America, all of which have put raw materials into their strategic agendas to secure access to raw materials. There is an indication of a surge of protectionism as the market areas aim to secure resources and economic gain in the global CRM value chains and developing a functional regulatory framework that responds to the sustainable use of CRMs in EV batteries in the global value chains is a major challenge.

China decided long before other economies to focus on the production of EVs and establish the associated supply chains, which has proven to be a successful strategy (Nakano, 2021). China is continuing its active resource policies as seen by Xi Jinping call in April 2020 to enhance the dependence on China in the global supply chains. China has also started to develop secondary applications of metals and enacted extensive policy and guidelines for recycling EV batteries and promoting second life uses. The policy directs manufacturers to design batteries that enable easier recycling and to provide technical information on proper storage and management. Furthermore, China places responsibility for recycling on the vehicle manufacturer, a mechanism known as “extended producer responsibility” (Ambrose and O’Dea, 2021).

The EU supports battery development through a range of initiatives (https://digital-strategy.ec.europa.eu/fi/node/423). In 2017, the European Commission set up the European Battery Alliance (EBA) to support the scaling up of innovative solutions and manufacturing capacity in Europe. The EBA connects stakeholders from science, industry, and politics with the aim of building and establishing a sustainable and competitive battery value chain in Europe. The activities of the EBA are complemented by other initiatives. In 2018, as part of the third “Europe on the move” mobility package, the EU adopted a dedicated strategic action plan on batteries, with a range of measures covering raw materials extraction, sourcing and processing, battery materials, cell production, battery systems, reuse, and recycling. In 2019, the European Commission launched Batteries Europe with the European Technology and Innovation Platform (ETIP) to coordinate and implement research and development activities along the battery value chain. Battery 2030+ initiative aims to coordinate the basic research. Important Projects of Common European Interest (IPCEI) promote research, development, and innovation along the entire battery value chain. In 2020, the European Commission published its proposal, a new Sustainable Batteries Regulation, as part of its wider strategy for a climate-neutral, resource-efficient EU economy. This proposal builds upon Directive 2006/66/EC on batteries and accumulators (the Batteries Directive) and will replace it. The proposal is geared towards modernizing EU legislation on batteries to ensure the sustainability and competitiveness of EU battery value chains. The proposal is an integral part of the European Green Deal and the first initiative of the European Commission on the Circular Economy Action Plan. The proposal aims to ensure that batteries placed in the EU market are sustainable and safe throughout their entire life cycle by establishing mandatory requirements, for example by mandating carbon footprint declaration for all the electric vehicle batteries placed into the EU market. It also sets concrete actions to promote circularity of CRMs by setting targets for recycled materials in new batteries and improved recovery rates.

In the United States, President Biden announced the *American Battery Materials Initiative* in October 2022 as an effort to mobilize the entire government in securing a reliable and sustainable supply of critical minerals used for power, electricity, and EVs. An ambitious goal is that half of all new vehicles sold in 2030 are electric (White House, 2022). In addition, the Infrastructure Investment and Jobs Act (IIJA, P.L. 117–58) includes multiple sections related to EV adoption and enhancing domestic supply of the critical minerals used in EV batteries (Tracy, 2022).

Global competition and protectionism raise debate about the differences in policies and regulation in different countries and market areas. For example, a major concern in Europe is the uneven operation environments for businesses due to varying national policies. In some markets, such as China, health, safety and environmental regulation on batteries and the prevailing working conditions are not as strict as in other countries. This may provide some financial competitive edge for Chinese companies, yet with social and environmental costs. Another concern for Europe is how the recent US Inflation Reduction Act of 2022 that provides financial support for, e.g., investments, will influence its competitive position in the global EV markets. The act also offers significant tax benefits to Americans who buy EVs under the conditions that the batteries “contain a level of critical minerals extracted or processed in any country the US has free trade agreement with or recycled in North America” (https://www.energy.gov/lpo/inflation-reduction-act-2022). In similar manner, Indonesia has recently discussed its plans to stop the export of nickel, to develop its own refinery and battery sectors.

Regulation and policies that have influence beyond borders are called for. At the international level, the Global Battery Alliance (GBA, 2020) is a public-private collaboration platform founded in 2017 at the World Economic Forum to help establish a sustainable battery value chain by 2030. This consortium develops standards for labeling batteries and sharing data, with the goal of providing access to critical information about battery chemistry and condition. Also, global climate targets, like the Paris agreement, have long determined the scope of climate policies of countries and supranational unions. The aim towards zero GHG emissions, particularly CO_2 emissions, has spread to all sectors of society, and the vital role of raw materials in reaching the targets has been acknowledged in national and institutional strategies.

In summary, the lack of effective global frameworks and governing bodies for evaluating the environmental and social impacts of global value chains of CRM foster protectionism and unsustainable geopolitical competition over CRM. As a result, the triple bottom line sustainability will be difficult to achieve in CRM, because market prices fail to account for the environmental and social costs associated with mineral extraction.

4.4. Circular economy of raw materials for electric mobility

Circular economy solutions are expected to reduce battery raw materials supply risks and provide solutions to sustainability challenges. A circular economy aims at keeping materials in use for longer times than currently by using recycled and secondary raw materials in processing, extending the lifetime of materials and products by improving their durability, replaceability, and repairability, repairing and reusing the products and, finally, recycling and recovering valuable raw materials, while simultaneously creating added economic value (Korhonen et al., 2018). Currently, the recycling rate of key elements in EVs is below 1 % (UNEP, 2013; EC, 2018). A revised and more coordinated policy and regulatory frameworks are needed to address recycling across the entire EV battery lifecycle – from raw material supply to end-of-life.

A fundamental question regarding the options for EV battery recycling is how long they last. The average lifetime of EV batteries (in the first application) is estimated to be approximately 10 years (Xu et al., 2020; Li et al. 2023), although the target life is 15 years (Deng et al., 2020). The end-of-life criterion for the first life of EV batteries is determined based on the state-of-health (SOH) rather than age: retirement threshold is 70–80 % of the initial capacity (Martinez-Laserna et al., 2018; Li et al., 2022). However, it is acknowledged that the SOH assessment and the related capacity calibration are not always straightforward and may require time and effort (Zhang et al., 2021). After their first life, EV batteries can be repurposed for second-life applications involving stationary energy storage. Indeed, it has been estimated that reusing them as energy storage for renewable energy could provide significant environmental benefits (Martinez-Laserna et al., 2018). For example, Philippot et al. (2022) have noted that repurposing end-of-life batteries could decrease the impacts on climate change by 16 %, while the corresponding reduction in acidification is 25 %. Several pioneering battery reuse projects are currently being developed in Europe.

After the efficient use and reuse of EV batteries, recycling batteries and battery materials reduces the need for primary mining and the environmental impacts of the battery value chain. While metals can theoretically be recycled indefinitely, their durability means they return for recycling slowly in practice. However, novel methods for forecasting the supply of recycled minerals are being developed. For example, the physical Stocks and Flows Framework (PSFF) is an integrated modeling and accounting method designed to track the dynamics of metal supply and demand at a global scale over long timespans (West et al., 2021).

In general, only a fraction of the energy is needed to recycle metals compared to a production chain that starts from mining. Furthermore, scaling up recycling will provide a significant new source of metals in the future. According to Gregoir et al. (2022) recycling could supply 45–77 % of battery metals (Li, Ni, Co) for EU by 2050. The recycling industry is aware that end-of-life lithium-batteries (LIBs) in electric vehicles pose a particular challenge that will only grow in scale in the future. The ReLiB project of Faraday Institution estimates that around 16,500 tonnes of battery packs will be processed by 2028 and the volumes will continue to rise thereafter as the first generation of EVs start to reach end of life in significant volumes (The Faraday Institution 2020, 1).

There are major variations in chemical composition and construction among battery types, depending on type, original purpose and size and the variations significantly affect what kind of recycling processes are available. The most common differentiation, also used in the EU Batteries Directive, is between portable batteries (used e.g. in consumer electronics known as 3C); automotive batteries (used for automotive starter, lighting or ignition power and traction batteries used in electric and plug-in hybrids); and industrial batteries (stationary storage). While recycling traditional lead-acid batteries (LABs) has been a common practice (Li et al., 2019), it is currently very limited for the newer lithium-ion versions used in EVs. It is hard to get detailed figures for the percentage of LIBs that are recycled, but it is often evaluated to be about 5 %. Recycling LIBs is technologically challenging, costly, and there are not yet enough LIBs in circulation for feasible recycling business (Neumann et al., 2022). Today, almost no lithium or graphite is recovered in the EU from batteries (or other sources) because the recovery processes have been deemed expensive compared to primary supply. In contrast, recycling efficiencies are estimated at about 95 % for cobalt and nickel, and 80 % for copper, depending on the utilized process. EV batteries are large and heavy, and made up of hundreds of individual lithium-ion cells, all of which need dismantling. They contain hazardous materials and have an inconvenient tendency to explode if disassembled incorrectly. Therefore, logistics and mechanical treatment of EV batteries require special attention and safety measures when planning and implementing recycling processes.

Public policy plays an important role in enabling the wider reuse of EV batteries and promoting the recycling of their constituent materials (Hu et al., 2024). Recent proposals from the EU suggest that EV suppliers would be responsible for ensuring the recycling of their batteries. Many car manufacturers have started to take steps towards this direction. For example, Nissan is now reusing old batteries from its Leaf cars in the automated guide vehicles that deliver parts to workers in its factories. Volkswagen is doing the same and has also opened its first recycling plant in Salzgitter, Germany, and plans to recycle up to 3600 battery systems per year during the pilot phase. As a first step, Volkswagen is focusing on cathode metals like cobalt, nickel, lithium, and manganese, while aluminum and copper are given into established recycling streams. Renault is recycling all its EV batteries, although as things stand, that only amounts to a few hundred per year.

Simultaneously, non-state EV battery actors around the world are drafting policies with targets for circular and responsible battery value chains. Regarding the reuse of batteries, a system for testing, evaluating and refurbishing batteries is needed (DeRousseau et al., 2017; Standridge and Hasan, 2015). This is also in the interests of major car manufacturers as Reinhardt et al. (2019) found that nearly all of them are currently participating in pilot and demonstration projects to explore the capabilities of second –use batteries and to develop viable innovative business models.

System-level aspects that future strategies for circular economy of EV batteries aim at a resilient supply of future battery materials without a need for additional encroachment of primary raw material reserves. The infrastructure for battery collection, reuse, repurposing and recycling requires a flexible flow of end-of-life batteries, a value-creating ecosystem, suitable business models and sharing information to ensure that owners, re-users and recyclers can access relevant information about battery systems (Reinhardt et al., 2019; Hossain et al., 2019; Jiao and Evans, 2016). In addition, clarifying the end-of-life battery ownership and liability requires explicit regulation in a circular economy of CRM in EV batteries (Jiao and Evans, 2016). Providing incentives and establishing requirements for sustainable practices "from mine to wheel" is necessary for achieving the sustainability goals in electric mobility and green energy society (Ambrose and O'Dea, 2021).

In summary, a circular economy in the CRM in EV batteries has great potential. However, the utilization of recycled materials in EV battery production is currently only marginally implemented, and the EV batteries lack design that would support end-of-lifecycle recycling in the future. Challenges in circular economy solutions in EV batteries include a high cost in recycling, transportation and storage of EV batteries, safety issues involved in handling of hazardous materials, and a lack of feasible business models and regulation to support a systemic change to circular economy in EV battery industry.

4.5. Emerging battery technologies

Advanced LIB technologies and technologies beyond lithium-ion will influence the demand for CRMs needed for batteries in the future. Cobalt is one raw material, the use of which has been already impacted. Currently there are existing solutions for Co-free cathode materials in

LIBs, containing mixes of lithium-nickel-oxide (LNO) or lithium-nickel-manganese-oxide (LNMO) as a new, high-voltage cathode active material (Välikangas et al., 2020; Lin et al., 2023). Furthermore, the already commercialized lithium iron phosphate (LFP) batteries are cobalt-free and have been estimated to be more ecological than NMCs across several categories (Lai et al., 2022).

Another CRM used in LIBs as an anode material, graphite, also faces pressures to be replaced. Several alternative anode materials have been investigated for graphite replacement, such as silicon, and simple binary transition metal oxides (Yao et al., 2020; Subramaniyam et al., 2016; Poizot et al., 2000), and even metallic Li for solid-state batteries. The use of biomass as a precursor material for carbonization of carbon, which has already been proven to be suitable battery anode material, is expected to become a viable solution in the short-term (Long et al., 2017; Soltani et al., 2021; Zhou et al., 2020). Biomass-based carbon materials are commonly classified into two main categories, graphitizable (soft carbons) and non-graphitizable (hard carbons) (Molaiyan et al., 2023). Due to the abundant nature of biomass, sustainability, renewability, and morphological and structural variety, it has become an extremely suitable candidate for fabricating advanced anode materials for high-performance batteries. The employment of biomass carbon anode materials, especially hard carbons, can speed up the development of greener energy storage technologies but can also effectively tackle the key issues regarding low-cost, high safety and energy density, and reduced dependency of CRMs. However, challenges related to correlation of biomass characteristics and related battery behavior, insufficient knowledge of biomass tailoring to correct particle morphology and pore geometry, and related mechanisms during the carbonization of biomass remain (Dou et al., 2018). Among the most advanced developments of biomass-based carbon materials for batteries is by a pulp and paper company Stora Enso that announced the development of hard carbon material produced from the Kraft lignin, currently under piloting stage (Sunila pilot, Finland). Biomass-derived carbon materials would not only be needed for partial graphite replacement in LIBs but also in the short-term as anode materials for Na-ion batteries in which graphite cannot be used (due to the inability of Na to form intercalation compounds under moderate conditions).

In addition to developments in battery materials, the existing cell manufacturing processes that typically use toxic solvents and halogenated binders or electrolyte salts, are being developed. These compounds pose challenges from the viewpoint of battery cell recycling and from an environmental and safety perspective. There are already known possibilities for greener cell manufacturing technologies, such as substitutes for NMP (N-methyl-2-pyrrolidone) solvent, halogen-containing PVDF (Polyvinylidene Fluoride) binder and/or electrolyte salt $LiFP_6$ (which also contains lithium).

Recently, Sliz et al. (2021), replaced NMP with DMF (Dimethylformamide) solvent, demonstrating that DMF can be considered as a valuable alternative to NMP without compromising the cell performance. Furthermore, this offered a significant fourfold reduction of energy needed to drying and solvent recovery, supporting reduction of GHG emissions during battery manufacturing. Recent improvements towards safer LIBs have also resulted in the development of solid-state batteries in which liquid electrolyte is replaced. Solid electrolyte would offer thermal and electrochemical stability for LIBs, as well as better cost-efficiency. However, solid-state LIBs are not CRM-free, and still require toxic chemicals, such as halogen-containing salts (Cavers et al., 2022).

Alternative battery technologies to LIBs have been developed already for some. In the short-term, Na-ion batteries are already in the early commercialization stage and appearing on the market, offering parallel energy storage technology for LIBs. This will affect especially the need for CRMs, since Na-ion cathodes can be prepared from abundant raw materials. Na-ion batteries have several advantages, but research and development are still needed to fully exploit them (Peters et al., 2019; Pu et al., 2019). While several companies are currently developing commercially viable Na-ion batteries, models with high energy densities, excellent electrochemical performance, and high stability are not yet commercialized although few companies have announced imminent productions. For example, Natron Energy (US start-up company) announced the development of ecofriendly and cost-efficient cathode materials for Na-ion batteries. This material is based on the Prussian Blue Analogue (PBA). More recently, CATL (Contemporary Amperex Technology Co., Ltd.) announced the first-generation Na-ion battery using Prussian white as a cathode material. This demonstrated an energy density up to 160 Wh kg^{-1} in the full cell operation (Gupta et al., 2022); for comparison, the corresponding energy density values for LIBs are in the range of 200–300 Wh kg^{-1} (Wang et al., 2022; Deng et al., 2020). If the cost of Na-ion batteries is further reduced, they will be favored also for energy storage in grids, where battery weight is not a key factor (Keller et al., 2016). Li-S and Li-air batteries are also considered as potential next-generation batteries in the longer term, offering excellent specific energies compared to traditional LIBs. However, they are not CRM-free, and improvements are also needed in the means of practical power and cycle life.

Additionally, technologies for refurbishing batteries are being developed fast. For example, EV batteries are suitable for storing renewable energy and balancing the peaks in energy consumption (Xu et al., 2023). As mentioned in the previous paragraph, also emerging battery technologies will be introduced to energy storage applications in the long-term, e.g., flow batteries, Li-S and Li-air batteries, and Zn-air batteries (Pellegrini et al., 2019). Significantly, these battery technologies can also be cobalt and nickel free. For example, organic flow batteries have been noted as one of the more promising options, as they can offer cost-efficiency compared to vanadium redox-flow batteries which use CRMs (Cao et al., 2020). However, while organic flow batteries hold potential for stationary energy storage, they are not considered as potential solutions for EVs.

It is emphasized that there are also other rapidly growing and relevant energy storage alternatives that could challenge the material demand for EV batteries, such as hydrogen technologies. In addition, the potentially significant V2G (vehicle-to-grid) technology is currently under development, which would allow the EV battery to be used as an energy storage for a home or even the electrical grid. If realized, EV owners could derive value from their batteries by reselling energy back into the grid when they are not driving, while also helping to balance societal energy consumption peaks.

In summary, alternative EV battery materials are needed but not enough attention has been paid to environmental and social impact assessment of these new battery metal technologies. Also, the increasing interest in new battery technologies runs a risk of decreased interest in developing circular economy solutions in battery metals.

5. Discussion

Our review on the five thematic issues regarding the sustainability of the use of critical materials in EV batteries demonstrates that the increasing demand for EVs necessitates sufficient availability of battery materials and clean energy along with socially and environmentally responsible extraction, production, and manufacturing practices and processes. In Table 1, we synthesize the sustainability tensions related to each thematic issue. Each theme involves wicked complexities that cross the three sustainability dimensions.

First, the complexity of sustainability tensions regarding resource sufficiency includes issues related to mining, processing, and the use of primary raw materials. Our review shows that the increase in demand for raw materials exceeds planetary boundaries, battery production relies on fossil energy, and the mining of raw materials may cause significant local environmental harm. Irresponsible mining may feed conflicts and endorse poor working conditions, particularly in the global South. The negative impacts and uneven distribution of environmental impacts and value generated by refining the mined metals (local vs.

Table 1
Sustainability tensions and interwoven complexity in global value chain of raw materials for electric mobility.

		Sustainability dimensions and interwoven complexity			
		Environmental	Social	Economic	Complexity
Domains of tension	Resource sufficiency	• Demand for raw materials exceeds planetary boundaries. • EV battery production is energy-intensive and relies strongly on fossil fuels. • Significant local environmental impacts at mining sites.	• Conflicts and poor working conditions are prevalent in mining regions in the global South. • Local opposition against new mining projects. • Large amount of mining is located on or near by indigegous peoples' land.	• Increased demand for critical raw materials. • Increased production and material costs. • Increased interest in investments.	• Lack of green and socially responsible mining in the conditions growing production of battery metals. • Uncertainty about sustainability requirements in the global metal markets.
	Global value chains	• Large carbon footprint of logistics due to the discrepancy between geographical locations of mining and mineral production.	• Uneven distribution of benefits and negative impacts (including local environmental impacts versus global climate benefits) on social well-being in the value chain.	• Limited volume and supply of raw materials limits key technologies in electric mobility. • Technological competition increases demand for CRMs. • Intellectual property rights slow diffusion of electric mobility innovations.	• Discrepancy between innovation in the global North and mineral extraction in the global South creates inequality in the distribution of benefits, negatively impacting global electrification.
	Regulation and policies	• Lack of global frameworks and governing bodies for evaluating the environmental impact of electric mobility.	• Lack of global frameworks and governing bodies for evaluating the social impact of electric mobility.	• Market prices fail to account for the true environmental and social costs associated with material extraction.	• Lack of commitment among the countries involved in EV value chains to effectively implement regulations, restrictions, and requirements. • Regulation and material extraction practices for EV batteries vary significantly across countries.
	Circular economy	• Utilization of recycled materials in EV battery production is only marginally implemented. • Current EV batteries lack design considerations for recycling.	• Health risks associated with handling hazardous materials in EV batteries. • Opposition from incumbents to the transition towards electric mobility.	• Recycling, transportation, and storage of EV batteries pose technological challenges and high costs. • Rapidly evolving technologies hinder the development of recycling business. • Recycling EV battery materials is not economically feasible.	• Lack of global norms and collaboration in battery ecosystems for recycling of EV battery materials.
	Battery technologies	• Alternative EV battery materials may create unseen environmental problems or shift existing problems to new locations.	• New technologies require new skills and training.	• Transitioning to new materials may disincentivize recycling of others.	• Rapid developments in battery technologies, material compositions, and second use applications require similar developments in recycling technologies.

global) may drive local opposition and prevent the establishment of new mines needed for the critical minerals. Paradoxically, the opposition may be stronger in the global North where EVs are used, where the local economic benefits of mining are often relatively lower, and local communities have better capacity to deny the extractive activities. Despite the potential barriers, the increased demand for critical raw materials will lead to a rise in material costs and increase interest in new mining projects, potentially even in socially and environmentally sensitive areas.

Second, the complexity in global value chains and logistics of battery metals stems from the current situation, where innovation, production and electrification of transportation occur in the global North while significant portion of mineral extraction takes place in the global South. The carbon footprint of logistics is large, because the materials are mined in different parts of the world where they are ultimately used. At the same time, there is an uneven distribution of benefits and harmful impacts on social wellbeing across countries participating in these value chains. The limited volume and supply of raw materials may become a limiting factor for the economic sustainability of key technologies in electric mobility. Furthermore, battery technologies are of strategic importance for companies and countries in technological competition, leading them to protect their intellectual property rights and slowing the diffusion of innovations.

Third, sustainability strategies, policies and regulation are only effective when they are implemented successfully. It is unlikely that all countries have the will or capacity to develop the needed regulation or can implement it effectively. The level of battery regulation towards sustainability varies significantly across countries. Thus, there is a clear lack of shared policy frameworks and governing bodies. Currently, the environmental and social costs of material extraction are not reflected in the market price. Thus, the markets alone do not create effective incentives for more responsible mining or manufacturing processes.

Fourth, the complexity in circular economy is present in organizing the recycling of battery metals efficiently and sustainably. Current EV battery production is utilizing only a marginal number of recycled materials and EV batteries are often not well-designed for recycling. For instance, the mistreatment of hazardous materials in EV batteries may cause health risks to personnel or damage the recycling machinery. Recycling, transporting, and storing EV batteries remains technologically challenging and costly. . Circular economy of battery metals takes time to establish, requiring sufficient flow of recycled EV battery materials to make it economically feasible. Consequentially, organizing the recycling of EV battery materials sustainably requires collaboration in regional and global battery ecosystems. However, the transition to circular economy in electric mobility can be actively hindered by actors benefitting from the existing system.

Fifth, the complexity of new emerging technologies refers to the rapid developments in battery technologies and material compositions, which may require new large-scale investments for manufacturing, and respective developments in recycling technologies and second-use applications. Furthermore, emerging chemistries that contain less CRMs may undermine the economic sustainability of recycling businesses if the content of valuable constituents is lowered. In the short term, the shift to new materials may hence disincentivize recycling, at least until the new materials also become scarce, rising their value. Transition to alternative battery materials may create new yet unknown environmental problems or move the existing problems to new locations. New technologies also require new skills and can be difficult to manage and govern.

There are several possible ways forward to address the above complexities and related challenges, which all have the features of wicked problems. They rise from the solutions which are aimed to mitigate the climate emissions in our traffic systems. When forming the framework, we have followed Jeff Conklin's (2005) idea about wicked problems. Features and dynamics of wicked problems can be understood best when we integrate them into the environmental, social and technical complexities.

Our literature review shows that in the long term, the overall raw material use must decrease. Further research into innovative high-performance battery chemistries or alternative energy storage technologies offer possibilities in this area. In this context, the discussion on sustainability often highlights the role of cobalt, its availability and the ethical aspects related to its processing chain. However, in some respects, cobalt has been overemphasized as a problem, as its use is decreasing in LIBs, especially with the introduction of new cobalt-free electrode materials. Cobalt can also be efficiently recycled from lithium-ion batteries like nickel. More research should be directed to diversifying global battery production geographically and in terms of raw materials used.

Research on the allocation of limited resources would support development of technologies that are not dependent on the scarcest metals, the known reserves or the currently available production capacity to meet the forecasted demand. Innovation research on the use of abundant versus critical raw materials would increase information about the possibilities of selective use of LIBs only in applications where other materials are not feasible. Furthermore, research on diffusion of innovation would support breakthrough innovations regarding the most critical materials, such as permanent magnets.

There is a continuous need to develop and research responsible mining and sustainable raw materials processing, especially in the global South. Research on effective verification of corporate social responsibility practices and the implementation of business ethics in battery metals value chains would produce valuable knowledge about the impact of global standards and guidelines. Research on transfer of knowledge and technologies and open innovation in global value chains and regional ecosystems would provide information on enablers and barriers of advancing sustainability in mining and raw material processing sectors. Research on business decisions and investors' reactions to investments in advanced green technologies is needed to better understand the criteria for green investment decisions.

Research on standards, regulation and battery strategies could address the predictability in global governance, regional regulation, and risk management in investments in sustainable use of CRM and circular economy in EV batteries. The implementation of the policies calls for multi-level governance research to better understand how global, national, and local contexts affect the alignment of policy guidance in terms of responsibilities and temporalities in decision making of the various governing bodies. Further analysis should identify more precisely the sanctioning and coordinating authorities at cross-national, national, and regional levels, possibilities for knowledge coproduction, framing of co-benefits, provision of capacity (technical, professional, and financial resources), and engagement of relevant stakeholders at various levels (cf. Homsy et al., 2019).

In addition to research on sustainable primary mining of critical metals, research on implementing the principles of circular economy in battery production is needed. This could involve technological research on reducing the size of batteries where feasible, extending battery lifetime, and facilitating second-life use (see Zhu et al., 2021) and recycling. Research on circular economy business models would increase understanding about the value creation and value capture in reuse, repurposing, remanufacturing, and recycling of battery metals. Furthermore, circular economy in battery metals calls for increased understanding about novel ownership models and data management and information openness across a battery value chain. Research on the dynamics of collaboration and competition in battery ecosystems and ecosystem management is needed to understand what creates incentives for collaboration in circular battery ecosystems. Attention has been given to the use of advanced technologies, but issues such as increasing sustainable innovation capacity through information and knowledge sharing, education, and cross sectoral collaboration could be further examined.

Further research on voluntary environmental policy instruments is needed to produce insights on emerging technologies and practices, such as digital product pass, that increase the openness of information across the whole value chain from mine to consumer and to support transformation to sustainable business in battery metals. Research on stakeholder roles in the EV battery production value chains is needed (Bridge and Faigen, 2022) to increase understanding about ways to support analysis of transparency in global value chains. Open information has a potential to create competitive advantage for battery metal produces who can verify that their products meet high ethical, environmental, and social sustainability standards. Finally, research on global development on technologies, agreements and practices would increase understanding about the catalyzing mechanisms of implementing responsible and sustainable practices in battery metals business.

6. Conclusions

Sustainable use of critical raw materials in electric vehicle batteries represents a topical yet sparsely researched subject. In this article, we have presented a transdisciplinary integrative literature review literature on sustainability and key thematic areas related to critical raw materials in EV batteries. As a result, we present a framework for addressing the complexity and wickedness of interwoven sustainability tensions regarding 1) resource sufficiency, 2) geographical distribution and global value chains, 3) regulation and policies, 4) circular economy, and 5) emerging battery technologies.

- In our analysis, we found the following complexities in the sustainable development of EV batteries: Lack of green and socially responsible mining in the conditions of growing production of battery metals.
- Uncertainty about sustainability requirements in the global metal markets.
- Discrepancy between innovation in the global North and mineral extraction in the global South creates inequality.
- Lack of commitment to implement sustainability regulations and restrictions.
- Lack of global norms and collaboration in battery ecosystems for recycling of EV battery materials. Rapid developments in battery technologies, material compositions, and second use applications require similar developments in recycling technologies.

The results of this paper have theoretical and practical implications for the ongoing discussion of sustainability of electric mobility through broadening the scope of issues and their interconnectedness. The comprehensive framework has relevance to the policies and management of EV battery industry, when considering solutions to sustainability challenges. It helps to identify and relate issues of environmental, social and economic sustainability and identify the fields of wicked problems. The identified complexities often cause wicked problems in practical real-life situations and justify stronger governance measures at global, EU and national level. The study also reveals vast areas where there is a need for further research in this rapidly emerging field. This study is not without limitations. First, we approached the sustainability of the use of critical materials in EV batteries mainly from the European perspective. We mitigated this limitation by analyzing how the issues connect to global aspects. Future research on the complexity of interwoven geopolitical sustainability tensions could examine the sustainability of the use of CRM in EV batteries from the North American and Chinese perspectives. Second, we have acknowledged that the relations within and between value chains co-evolve with geographical and geopolitical factors across different scales, but further study on the impact of geopolitics on sustainable EV and battery production is needed. Thus, the thematic areas covered in this paper are not exhaustive but limited by the scope of the study.

The policy implications of our study comprise insights into sustainability of electric mobility. First, it recommends approaching any seemingly simplistic solutions to the use of CRMs in electric mobility with a healthy dose of skepticism in regional and national governance. Our results indicate the importance of multi-level governance and holistic perspectives as a realistic pathway for achieving more sustainable use of CRMs. Due to the inherent complexity of sustainability and the global scope of the use of CRM, the global, national, and regional levels of policy making can use the sustainability framework presented in this paper in evaluating the sufficiency of policy measures. Second, our study highlights that many of the sustainability challenges need solutions that build on a combination of technological and social problem solving, such as coordinating global and cross sectoral value chains to transition towards more ecologically sustainable battery materials. The results of this study support reducing the ubiquity in the terminology in the Environmental, Social and Governance (ESG) framework with respect to CRM. Also, the discussion on the inherent complexities across the sustainability dimensions supports creating a common language for aligning actions with specific United Nation's Sustainability Development Goal (SDGs) in battery metals industry. Third, the results of this study provide valuable insight for policy making on the efficient and feasible recycling systems for EV batteries in the future. The transition to circular economy in battery metals is evolving rapidly, and taking sustainability aspects into account will support the mitigation of negative environmental and social impacts of circular economy solutions.

CRediT authorship contribution statement

Hanna Lehtimäki: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Marjaana Karhu:** Writing – original draft, Formal analysis, Conceptualization. **Juha M. Kotilainen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Rauno Sairinen:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ari Jokilaakso:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ulla Lassi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Elina Huttunen-Saarivirta:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

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

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