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Review

Recycling or Sustainability: The Road of Electric Vehicles Toward Sustainable Economy via Blockchain

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Abstract: This semi-systematic review paper discusses four research questions based on findings from the last 10 years: What are the crucial issues in the ongoing debate on the development of the electric vehicle (EV) concept? Where are the major conflicting points and focuses between sustainable economy and EVs? How does the mining of metals and minerals follow current zero-waste sustainability trends, and how does the prediction of the magnitude of the future demand for EV batteries guide strategic decision-making in policies throughout the globe? As it is not easy to currently predict how metals necessary for EV productions will be produced, this article suggests a strategy that is diverse regarding its approaches to shaping the sustainable mining and further development of EVs, along with the involvement of urban planning. Using broad literature and a published pool of prediction scenarios, we provide a comprehensive assessment of future EV battery raw materials development under a range of scenarios, accounting for factors such as developments in battery technology, variations in the EV fleet composition, sustainability aspects of development of second use and recycling technologies. Additionally, this paper demonstrates how blockchain technology is likely to force mineral and metal supply chains to become significantly more traceable and transparent.

Keywords: electric vehicle; mining; blockchain; sustainability

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1. Introduction

As the global shift toward sustainable transportation continues, understanding the geographical distribution of these critical metals has become increasingly important as the mining of cobalt, lithium, nickel, and other critical metals often occurs in regions with weak environmental regulations and human rights protections, leading to the exploitation of workers, contamination of local ecosystems, and displacement of Indigenous communities [1]. Furthermore, the energy-intensive nature of metal refining and the potential for toxic waste from mining processes can contribute to greenhouse gas emissions and other forms of environmental degradation [2,3]. Standardized manufacturing guarantees that electric vehicle (EV) components meet performance and safety standards, while regulations ensure the safe handling of hazardous materials, such as lithium-ion batteries, to protect both workers and the environment [4].

The establishment of uniform laws and regulations for metal trade and recycling is crucial soon to effectively assess and mitigate potential supply risks and social–environmental impacts [5,6]. Standardized frameworks will ensure responsible sourcing, promote sustainability, and enhance the transparency of global metal markets, fostering a more resilient and ethical supply chain [6,7]. While addressing climate change, the electric car revolution has the potential to have a negative impact on sustainable mining and the metal industry, increasing pollution die to unsustainable mining and putting extra costs and waste in raw materials extraction necessary for EV production [8,9]. However, recent developments in blockchain technology and its application across all industries and economies can have a positive impact on these developments [5,10]. Hereby, in addressing critical aspects of electric vehicle development, blockchain technology has a readiness level to be applied in all aspects of mining and metal production, logistics, and trade [10–12]. This paper analyzes the latest publications and predictions on key technologies, battery materials, and global trade up to 2050, offering insights into future mineral demand driven by the electric vehicle fleet and battery chemistry developments. We examine how blockchain can enable environmentally friendly metal supply for EVs and enhance transparency in supply chains, enabling standardizations and regulations globally. The research reviews predicted EV battery material demand over the next 25 years, focusing on mining regions, unethical metal production, blockchain adoption, and the impact of the EV revolution on sustainable development and regulations [1,4,7,10].

This paper aims to provide answers to the following questions:

(i) What are the crucial issues in the ongoing debate on the development of the electric vehicle concept?
(ii) Where are the major conflicting points and focuses between sustainable economy and electric vehicles?
(iii) How does the mining of metals and minerals follow current zero-waste sustainability trends?
(iv) How does the prediction of the magnitude of the future demand for EV batteries guide strategic decision-making in policies throughout the globe?

This article recommends a strategy that is diverse regarding its approaches to shaping the sustainable mining and further development of electric vehicles, along with the involvement of blockchain, ensuring transparency and sustainability in the EV industry.

It is structured as follows:

After introducing the topic, in the second part, focus is given to issues evidenced regarding EVs in the current context. The third part analyzes blockchain technology with a special emphasis on metal recycling. In the fourth section, EVs on the road to a sustainable economy are examined, including sustainable practices in EV production via a balanced economy, regulations for the sustainability of EVs, and key challenges in international standardization in the EVs field. Finally, conclusions are provided.

2. EVs in Today's Context

The top two global issues that need to be addressed in the coming years are those related to energy and the environment [2,5,9]. EVs are becoming more popular for many reasons. One of them is that their role in lowering greenhouse gas emissions is the most notable [4,10]. Although remanufacturing has been recognized as a practical and sustainable solution to address these problems, there has not been a thorough examination of how Industry 4.0 technologies can best support this process in the literature [12]. The next question is how to quantify the future demand for battery materials due to the shift to electric vehicles [1,10]. Another concern is the growth of demand for electric vehicles and trends in the consumption of electric light-duty vehicles [7,9]. Understudied are current developments in mining and metals for environmentally friendly transportation, too. Also, there is still a lack of research on identifying the areas with abundant metal deposits that are essential to producing electric vehicles.

2.1. Toward Industry 4.0 and Beyond

Modern industry stands at the cusp of a new era, referred to as Industry 4.0, characterized by the widespread implementation of technologies such as 3D printing, wireless communication, artificial intelligence, and the IoT—Internet of Things [13,14]. This technological evolution has directly impacted the mining industry as it grapples with the challenges of increased efficiency, safety, and sustainability [10,13]. In the mining sector, demand for EVs drove the urge for deeper mining, coupled with the need to optimize these operations under the constraints of the Paris Agreement, which made a fundamental shift in mining practices and techniques [6,8,15,16]. To address these challenges, mining companies have turned to innovative solutions, such as the introduction of electric vehicles for extraction and transportation at the mining sites and the integration of smart mine networks powered by blockchain technology [5,11,17,18]. The mining industry's resilience and adaptability have been on full display as it embraces the opportunities presented by Industry 4.0 [19–21].

However, the transition to a fully digitized and sustainable mining industry faces significant challenges, particularly in the sustainable extraction of materials for EV batteries and ensuring transparency across production, transportation, and trade [8,15,17]. The World Bank has noted the low maturity of that novel industry and the high difficulty in implementing these transformative technologies across the sector [22–24].

As the mining industry navigates this transition toward a new era of EVs, it must not only focus on increased efficiency and productivity but also on the environmental and social implications of its operations [14,25,26]. The concept of "Mining 4.0" has evolved to encompass not only technological advancements but also a commitment to environmental sustainability and social responsibility [17,19,27,28]. By aligning their efforts with the principles of a circular economy and sustainable development, mining companies can ensure that the industry's transformation benefits both the bottom line and the communities in which they operate [3,13,15,28,29].

The future of the mining industry lies in its ability to seamlessly integrate technological innovation with a holistic approach to sustainability, paving the way for a more resilient, environmentally conscious, and socially responsible sector, as presented schematically in Figure 1 [17,20,30,31].

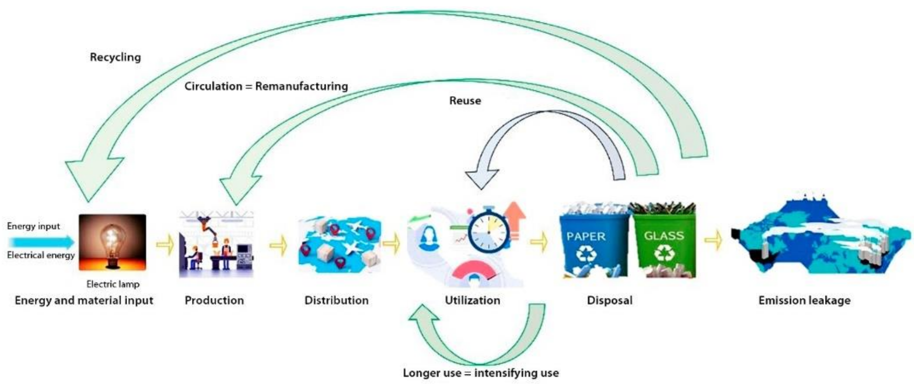

Figure 1. Schematic presentation of the modern mining industry providing energy-driven materials.

2.2. Quantifying the Future Demand for Battery Materials in the Shift to EV

The supply chains for the critical minerals used in batteries vary geographically, though a few countries have a dominant role in the production of key minerals [13,25,32,33]. Today, electric vehicle batteries primarily use lithium-ion chemistries for lithium-ion cathode materials that are NCA (Li-NiCoAl oxide), NCM (Li-NixCoyMn1-x-yO2), and LFP (Li iron phosphate) [34]. These batteries rely on varying amounts of four critical metals, Li, Ni, Co, and Mn, as identified in studies on mineral criticality for battery cathode materials [35,36]. Additionally, there is discussion about other minerals that may become critical in the next decades, as well as for other battery chemistries currently under development [16,19,37,38]. The most significant decision in battery production is the selection of cathode material, which accounts for over half the cost of a battery cell and influences important characteristics like energy density and charging speed [16,26,39,40]. While the anode (typically graphite) and electrolyte (usually Li salt solutions) also face supply chain vulnerabilities, the options for these components are more limited, offering fewer opportunities to mitigate risks by changing technologies [39–41]. Due to limited production data, these components were not included in the scope of our evaluation [42–44].

The mining industry has been forced to adopt blockchain technology to address these difficulties by requiring transparency and stronger environmental, social, and governance (ESG) compliance regulations [27,32,35,37].

2.3. The Rise of EVs: Trends in Electric Light-Duty Vehicles

China's EV market has undoubtedly been a global powerhouse, with the country accounting for half of the world's electric cars sold in 2024 [36,45,46]. Hence, the EV industry is emerging in Europe as highly dynamic, bringing new markets and key producers, creating competitiveness on a global scale in the electric car market that brings continuous development of more affordable models [45,47]. Nowadays, China still dominates the production and sales of EVs on the global market, with Europe reaching a significant lead in total car sales and a large share of existing car inventories [47,48]. As the demand for electric vehicles and energy storage systems continues to grow, the pressure on the supply of lithium and other critical raw materials has intensified [49]. This rising demand has led to concerns about the availability and sustainability of lithium. Similarly, the price of lithium carbonate, a crucial material for lithium-ion batteries, has been a significant concern in the global energy storage market. Despite China's ambitious EV development plans, progress lags due to challenges, such as remaining high battery costs on a global scale.

The price of lithium carbonate, a crucial material for lithium-ion batteries, has been a significant concern in the global energy storage market. In recent years, China has experienced a notable decline in lithium carbonate prices, raising questions about the long-term viability of battery material costs. The decline can be attributed to several factors. Firstly, the Chinese government has implemented policies to promote the domestic lithium industry, including incentives for mining and processing. Additionally, increased investment in lithium extraction and processing technologies has resulted in improved efficiency and lower production costs.

Another contributing factor is the global battery market's shift toward alternative battery chemistries, such as sodium-ion batteries, which may offer a more sustainable and cost-effective solution. Despite the decline in lithium carbonate prices, battery material costs remain a significant issue in the energy storage industry [49]. Despite the global economic turbulence and supply chain disruptions experienced, the EV market in China continued to demonstrate remarkable growth, shattering previous sales records encompassing both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) [49,50]. The rapid adoption of electric vehicles has been driven by a confluence of factors, including the introduction of new mass-market models, improvements in technical performance, and cost reductions [9,45,48].

China's strategic approach to driving the adoption of EVs has been a subject of significant interest and analysis, with electric vehicle sales experiencing a remarkable increase in 2024, with battery electric vehicle (BEV) sales growing by 110% compared to 2021, reaching 11 million units with plug-in hybrid electric vehicle sales tripled [45,48,51].

At the same time, major EV carmakers, especially in Europe, are putting enormous investments and efforts to compete on a global scale with promising products such as fully electric fleets, cheaper cars, and greater investment integrating vertically with the mining industry to enable cheap, fast and sustainable key minerals for battery-making [48,50]. This situation enables global consumers to choose from various options of ever-increasing electric car models that reach 500 in 2022, more than double the options available in 2018 [45,47,51].

The faster growth in plug-in hybrid electric vehicle sales relative to battery electric vehicles requires further research, as plug-in hybrid electric vehicle sales still remain lower overall and are catching up on the post-COVID-19 boom [45,47,51]. Battery electric vehicle sales in China tripled from 2020 to 2023 after moderate growth over 2018–2020, indicating a significant shift in consumer preferences and market dynamics. China's dominance in the global electric vehicle market is further highlighted by the fact that the country accounted for nearly 60% of all new electric car registrations globally in 2024 [49,51]. China has been the center of attention in the EV space over the past decade, with bold moves to transition toward cleaner transport and energy systems and effectively ensuring its status as the most critical player in the global EV supply chain [50,51].

Despite China's ambitious goals for developing and deploying electric vehicles, progress has failed to reach planned targets because of EV industry challenges, similar to those in Western countries, such as high battery costs and lack of a clear infrastructure model for vehicle charging [46,48,52,53].

However, Europe has established its own areas of dominance, particularly in the Nordic countries, where EVs accounted for more than half of all cars sold in 2024 [47,54,55]. In Europe, the EV market has been experiencing rapid growth, with the region expected to lead sales of EVs, potentially overtaking China around 2028 [47,55]. Europe's success in the EV market can be attributed to a combination of factors, including generous subsidies, supportive policies, and a strong focus on sustainable mobility [45,53]. Norway has emerged as a leader in the electrification of transport, with nearly 79% of new passenger cars sold being EVs in 2024 [56].

The regional differences in EV adoption are also reflected in the technology choices made by original equipment manufacturers (OEMs) [2,45,50,51]. While China has maintained its dominance in the supply of critical components, such as battery manufacturing, Europe has been able to establish its own niche in the EV market [48,54,57]. The analysis of the electrification portfolio choices of major automotive manufacturers across different regions suggests a trend toward SUVs for both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), with regional variations in battery chemistry choices as presented in Figure 2 [58,59].

Across the first six months of 2024, global EV sales increased by 26 percent, while preliminary data suggest that sales increased around 30 percent in September, slower than in the previous years—which included a 33 percent increase in 2023 and 60 percent in 2022—but off a higher base [59]. These numbers include both battery EV and plug-in hybrid EV (PHEV) models, which reflects one of the stories being told this year, with numerous companies ditching purely EV targets and refocusing, in the near term, on PHEVs. Carmakers around the globe are adjusting EV targets to allow for increased demand for PHEVs, including Jaguar Land Rover, Volvo, BMW, Toyota, Ford, and General Motors [59].

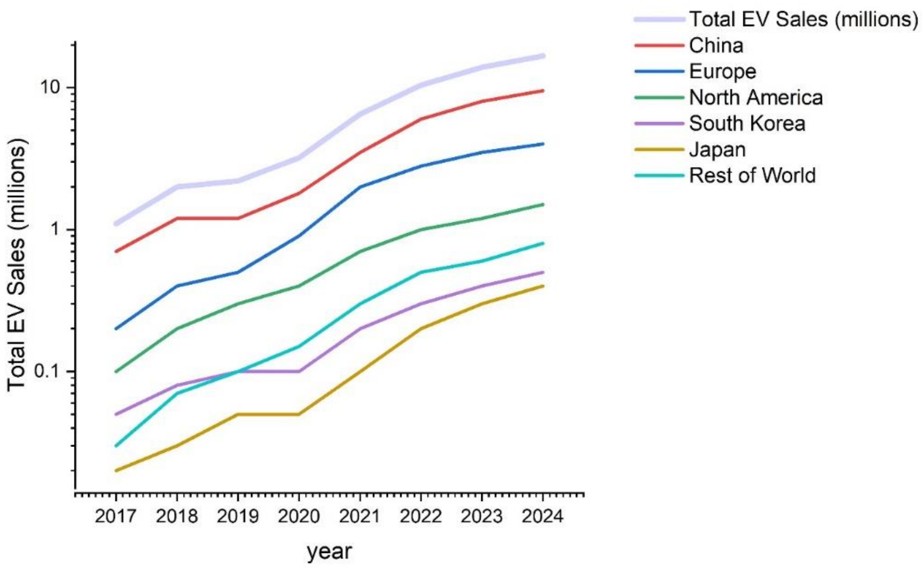

Figure 2. Battery electric and plug-in hybrid vehicle sales across markets during the period 2017–2024. Modified from references [59–61].

The shift toward EVs represents an important transformation in the global automotive industry, driven by the urgent need to address climate change and reduce reliance on fossil fuels [2,9,58,59]. However, the sustainability of this transition depends not only on the adoption of EVs but also on establishing a resource-balanced economy that includes the efficient use of critical raw materials and comprehensive recycling strategies, particularly for metals [60,61]. The complexity of the EV industry lies in its heavy reliance on a range of essential metals for batteries and functionality, including Li, Co, and Ni, as well as Cu for electrical wiring and Al for light-weight construction [3,16,40,62]. The supply of key metals necessary for the development of batteries imposes challenges that are related to geopolitical risks, supply chain vulnerabilities, and environmental concerns related to mining practices, which pose threats to the stable and sustainable supply of these materials [62–64].

An example of poor resource management is seen in cobalt mining sites in the Democratic Republic of Congo, where mining has led to severe human rights abuses and environmental damage [16,29,64]. Sustainable resource management can be achieved not only through mining but also through circularity and recycling [65,66]. Recycling metals, especially from spent lithium-ion batteries, offers a viable solution to reduce the demand for rare metals and mitigate the environmental impact of mining [65]. Up to today, there are two key strategies for obtaining metals necessary for new battery production: (i) recycling spent lithium-ion batteries to recover essential metals and (ii) vehicle recycling to recover aluminum [61,65,66].

The battery supply chain can be divided into three segments: (i) upstream (mining and extraction of raw materials), (ii) midstream (processing these raw materials into battery-grade components), and (iii) downstream (cell and pack manufacturing, as well as end-of-life recycling and reuse) [66]. In 2020, most of the lithium used in battery production was extracted from Australia (49%), Chile (27%), China (16%), Argentina (7%), and the U.S. (1%), with percentages rounded to the nearest point [65–67]. Most countries processed their extracted Li, except Australia, which sent 99% to China and 1% to the U.S. due to its spodumene rock requiring foreign refining. China uses 31% of its raw lithium, and Chile uses 3% for non-battery purposes, while the rest is refined into battery-grade Li by China (59%), Chile (29%), Argentina (9%), and the U.S. (3%). Chile's reported imports and exports exceeded production, causing discrepancies [68,69]. Refined lithium was then traded to China (55%), South Korea (16%), Japan (12%), the U.S. (5%), Canada (1%), and others (12%) [69]. Not all of the Li was used in battery cathode production, with significant portions used in non-battery products, such as 41% in China, 44% in South Korea, 29% in Japan, 95% in the U.S., and 55% in Canada [70,71].

A significant amount of Co, Ni, and Mn is used for products other than batteries [71,72]. Notably, a large amount of Ni and Mn is transformed into non-battery products, limiting the influence of major producers like Indonesia, Australia, and Gabon on battery material supply chains [68,72,73], as presented in Figure 3.

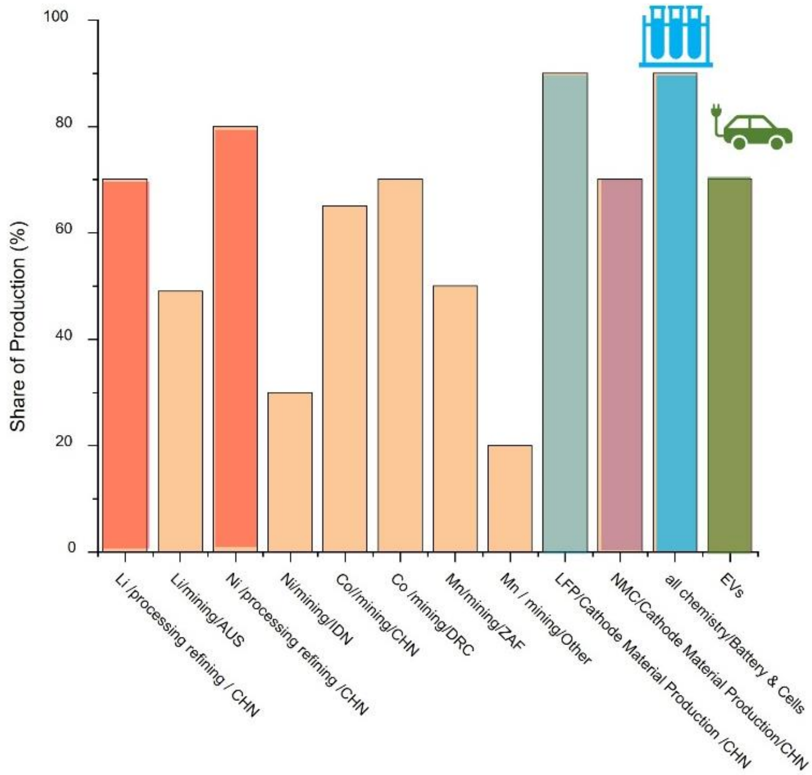

Figure 3. Distribution of EV battery and material supply. Modified from [73].

2.4. Trends in Modern Metal Mining Industry for Sustainable Transportation

Globally, automotive manufacturers are increasingly managing their material supply chains as they design batteries for their vehicles [55,74,75]. The trend will drive significant growth in Li, Co, and Ni mining, with global supply chains requiring new resource discoveries, thereby increasing uncertainty around the development of EVs and their crucial battery capacity requirements [55,58]. In our analysis, we rely on a most probable trend that will continue the domination of Li-NiCoMn oxide (NMC) batteries and increase demand over 20 times for Li, in the range of 17–19 for Co, 28–30 for Ni, and 16–20 for other materials for next 25 years, i.e., by 2050 [34,68,73].

In the case scenario where other battery chemistries, such as lithium iron phosphate or novel Li-S or Li-air batteries, will be adopted at a large scale, the demand for Co and Ni would be smaller, as presented in Table 1 [71,72]. This table presents the most likely chemical composition of the batteries if the current trend of widespread utilization of lithium nickel cobalt aluminum (NCA) and lithium nickel cobalt manganese (NCM) batteries (referred to as the NCX, with X = either Al or Mn) continues. Battery producers are aiming to replace costly Co with Ni, leading to the development from NCM111 to NCM523, NCM622, and NCM811 batteries (the numbers denote ratios of Ni, Co, and Mn) and NCM955 (90% Ni, 5% Co, 5% Mn), expected to be available by 2030 [41,72,74].

Table 1. Composition of cathode and anode materials in modern EV car batteries [37,72,74].

Type	Label	Composition (%)	Explanation
NCM	NCM 622	60/20/20 (Ni/Co/Mn)	Cathode 60% Ni, 20% Co, 20% Mn.
	NCM 523	50/20/30 (Ni/Co/Mn)	Cathode 50% Ni, 20% Co, 30% Mn.
	NCM 111	10/10/10 (Ni/Mn/Co)	Cathode Ni, Mn, Co (1:1:1 ratio).
	NCM 622-GL	60/20/20 (Ni/Mn/Co)	Cathode NCM 622 with graphite layer.
	NCM 811-GL	80/10/10 (Ni/Co/Mn)	Cathode 80% Ni, 10% Co, 10% Mn with graphite layer.
	NCM 955-GL	90/5/5 (Ni/Mn/Co)	Cathode 90% Ni, 5% Co, 5% Mn with graphite layer.
Other	NCA	Li, Ni, Co, Al	Specific weight ratios of lithium, nickel, cobalt, and aluminum as cathode.
	LFP	Li-Fe phosphate battery	Lithium iron phosphate as cathode.
	Graphite (Si)	Graphite anode + Si	An anode is graphite with silicon to enhance performance.
	Li-S	Li-S battery	Cathode of Li and S.
	Li-	Air lithium–air battery	Lithium is used as the anode, and oxygen from the air as the cathode material.

The material requirements for batteries in the next years depend on the development of battery chemistry and key technologies and formulations. As shown in Figure 4, about 6–12 TWh of battery capacity will be needed annually as a result of the growth of the EV fleet and the required battery [9,71,72]. It is expected that specific energy for battery packs will range from 160 Wh/kg for NCM111 to 202 Wh/kg for NCM955-Graphite (Si) batteries in typical mid-size EVs, with lifespans expected to increase to 15 years [32,40,41,74]. In the coming decades, the use of LFP (LiFePO4) batteries is expected to grow, as besides their weaker efficiency due to lower energy density, to that of NCA and NCM batteries, they offer advantages like lower production costs due to abundant materials, better safety from improved thermal stability, and a longer lifespan [71,75].

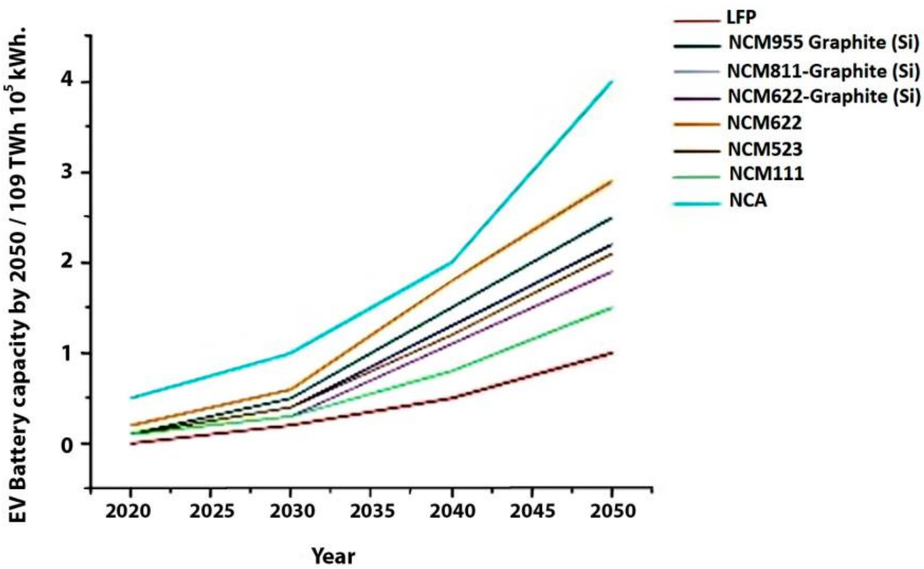

Figure 4. Battery market shares and yearly EV battery sales until 2050 for the fleet development in the STEP scenario, modified from results obtained from references [72,75].

2.5. Identifying the Regions with Abundant Metal Deposits Critical for EV Production

This geographic concentration of supply, coupled with the expected continued growth in electric vehicle adoption, raises concerns about potential supply shortages and price volatility in the future. Africa is currently a global powerhouse in the production and supply of critical minerals essential for the manufacturing of EVs and their battery systems [32,64,75,76]. The mining of cobalt, often performed in the Democratic Republic of Congo, has been linked to child labor, unsafe working conditions, and environmental degradation [3,27,77,78]. However, the increased demand for Co has also raised concerns about the environmental and social impacts of mining in the region, where children are injured and killed in mines located in areas characterized by poverty, criminality, and corruption [70,78,79].

Graphite is used in Li-ion battery anodes and other EV components, and Mozambique and Madagascar are major graphite producers, with significant reserves in Tanzania [80,81]. Manganese is important for EV battery cathodes and other clean technologies, with the largest reserves found in South Africa, accounting for almost 44% of global Mn production [72,82]. South Africa also produces nearly 44% of global Cr, which is key for renewable energy plants and nuclear power [83]. Other African continent countries such as DRC, Namibia, and Zambia have significant reserves for Cu production, which is essential for EV wiring and electrification [84]. While Li production in Africa is currently limited, countries like Mali have significant Li reserves that could be tapped for EV battery manufacturing [68,85]. It is expected that the global EV industry reach USD 300 billion (about USD 920 per person in the U.S.) by 2050. The supply of these critical minerals from Africa will be crucial to support the transition to electric mobility [58,70,73,78].

Metal recycling has a lower environmental impact compared to mining and processing new metals [3,6,71,85,86]. Advancements in battery technology and increased recycling efforts may help ease supply issues, but they are not a complete solution; only responsible recycling practices—with proper waste management, worker protection, and environmental controls—can ensure true sustainability [65,87–89]. In the metal recycling center, inputs and outputs need to be continuously updated, while transportation and logistics details are added as partners contribute along the supply chain route [90–92].

3. Blockchain Technology

Blockchain technology, initially developed for cryptocurrency (e.g., Bitcoin), reduces reliance on cash transactions and speeds up processes traditionally delayed by financial institutions [13,18,23,93,94]. Cryptography ensures the security and confidentiality of information in many industries, and it is significant in mining as it addresses integrity, non-repudiation, and authentication in data sharing [18,20,95]. Blockchain transactions are verified through nodes, grouped into blocks, and linked via unique identifiers called hashes [21,43]. Each block's hash is a fingerprint that ensures the integrity of data, and any change occurring in the block alters its hash, thus ensuring secure, traceable, and immutable records in the blockchain, as presented in Figure 5 [5,20,21].

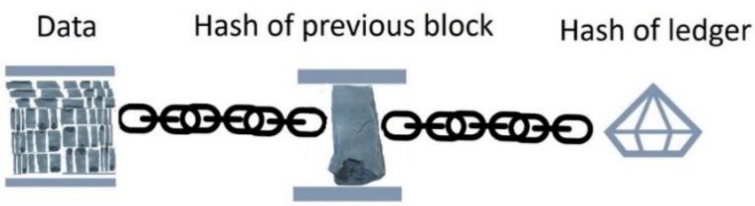

Figure 5. Schematic presentation of traceable hash elements within distributed ledger within blockchain.

Control and decision-making transition from an individual or group to the whole network of participants in the blockchain is referred to as decentralization [5,95–97]. The need for a decentralized system in blockchain has been developed to overcome vulnerabilities of a traditional, centralized fund transfer system in which the bank, as a central authority, controls the entire transaction process [18,21,98]. To address such limitations, the idea of a decentralized system is introduced in which data are stored, recorded, and synchronized at separate places, bringing better clarity and improving trust among the stakeholders whilst simultaneously deterring participants from applying authority and control over other members of the blockchain network [98,99].

The mineral and metal industry has long faced ethical sourcing challenges due to complex and opaque supply chains obscuring raw material origins and production methods [18,23,98]. Blockchain technology offers the potential for transformative improvements in sustainability and transparency in metal mining and recycling industries, enabling sustainable practices and reducing potential conflicts [5,20,100,101].

When incorporating used metal mixtures into new vehicles, it is crucial to verify the authenticity and composition of these materials, and only with the use of blockchain technology is it possible to ensure verification of the origin and authenticity of metals used in electric vehicle production [14,17,25,100]. By providing a secure, transparent ledger, blockchain records the provenance, composition, and quality of metal mixtures, preventing the use of counterfeit or substandard materials [14,94]. This traceability supports the sustainable and ethical sourcing of raw materials and enables the tracking of recycling and reuse, promoting a circular economy and reducing environmental impact [5,27,30].

Beyond mineral processing and mining activities, blockchain incorporates supply chain transactions and tracks items from store to store using verified identities for online banking, ecommerce, and others [24,100,101]. Other applications are e-voting and remote participation in forums where critical decisions are made, health records for more control of data, which can improve health status, copyright protection, decentralized finance (DEFI) to recreate traditional finance systems such as loan and insurance applications [5,23,102,103]. For successful technological development, apart from maintaining and safeguarding corporate and personal information, it is also important to motivate employees in their daily duties, and in this context, blockchain appears as a quicker, more effective solution for an employer–employee relationship with a management system that contains all credentials of job prospects [23,104–107]. Such operations are time and money-wise sustainable solutions, checking on job candidates' training, credentials, work history, or talents [5,13,95,105]. Furthermore, they simplify complex international payroll transmission, enabling more efficient and timely cross-border payments to multinational employees and improving working conditions [11,19,42].

Integrating blockchain technology can significantly enhance the sustainability and transparency of the electric car industry [103,108]. The production of electric vehicles requires a significant amount of metals, such as lithium, cobalt, and rare earth elements, which are often associated with environmental and social concerns. The most important area where blockchain can contribute to the sustainability of electric cars is the sourcing and traceability of raw materials, particularly metals [39,43,94].

In the transportation of metal and EV, the synchronized nature of blockchain informs the global ecosystem and opens the possibility for faster agreement if there exist changes in the trade chain, such as a shipping route or timetable [5,17,53,96]. This synchronization simplifies the resolution of problems and provides solutions, enabling precise data management within the blockchain and a decrease in conflicts. All parties involved in the larger value chain, including raw materials providers, financial institutions, logistic company owners, research laboratories, warehouses, and customers, can be part of a single blockchain [5,6,18,96]. This promotes innovation and compliance within all sectors and industries outside of mining and smelting of recycling metals [10,67,93,98].

Environmental, social, and governance (ESG) challenges, including environmental degradation, human rights violations, and weak governance, persist in global supply chains despite regulations like the EU Conflict Minerals Regulation [18,93,99,108]. Blockchain's secure, immutable ledger can enhance transparency and accountability by tracing the provenance of raw materials, particularly conflict metals, while its integration with AI can further optimize supply chain efficiency, from ore tracking to worker identification and access control [10,13,18,95].

Blockchain in Metals Recycling

In the sustainable, organized recycling metal center, both inputs and corresponding outputs are continually updated throughout the whole EV production and recycling supply chain [3,6,18,30]. Additionally, transportation information and logistics details from partners along the supply chain are automatically updated and visible to permitted participants with each new transaction [21,26,109]. This allows regulators and end users to verify data, as the lack of connectivity between participants outside of the institutional system is a key challenge. The proposed metal recycling blockchain system, from waste collection to the recycling facility, is presented schematically with the diagram shown in Figure 6.

Utilization of blockchain through the whole supply system, from the mining industry through the production of EVs and recycling of metals, is a solution that addresses a major concern inherent in the modern supply chain (SC) that they are designed as standalone and discrete systems that fail to connect actors outside SC institutions [104,107,108]. Recycling EV batteries is crucial for recovering valuable metals like lithium, cobalt, nickel, and copper, creating a sustainable supply chain, and reducing dependency on limited natural reserves. Recycling EV batteries minimizes the environmental impact of battery disposal, preventing toxic materials from polluting ecosystems whilst supporting a circular economy by reintroducing recovered materials into production, promoting sustainability in the EV industry [1,6,52,66,97]. Therefore, blockchain offers solutions for controlling various aspects related to processing ores and machinery in the mining industry, as visually presented in Figure 7.

The adoption of blockchain technology in the electric vehicle supply chain holds immense potential, offering enhanced traceability, security, and transparency. Additionally, the technology can promote energy democratization, allowing small-scale renewable energy producers to directly access the energy market and sell their excess energy, contributing to a more equitable and diversified energy landscape. However, implementing blockchain technology in the EV supply chain is not without its challenges, obviously related to the immaturity of the technology itself, as it remains a relatively new and evolving field. Another key challenge is the integration of blockchain with existing supply chain systems and processes. For the successful implementation of blockchain in the EV supply chain, barriers, such as the lack of industry standards, data governance issues, and the need for significant infrastructure investments, need to be addressed.

Furthermore, the adoption of blockchain technology in the EV supply chain faces data privacy and security challenges. The decentralized nature of blockchain raises concerns about data protection and compliance with regulations, which must be carefully navigated to ensure the integrity and confidentiality of sensitive information.

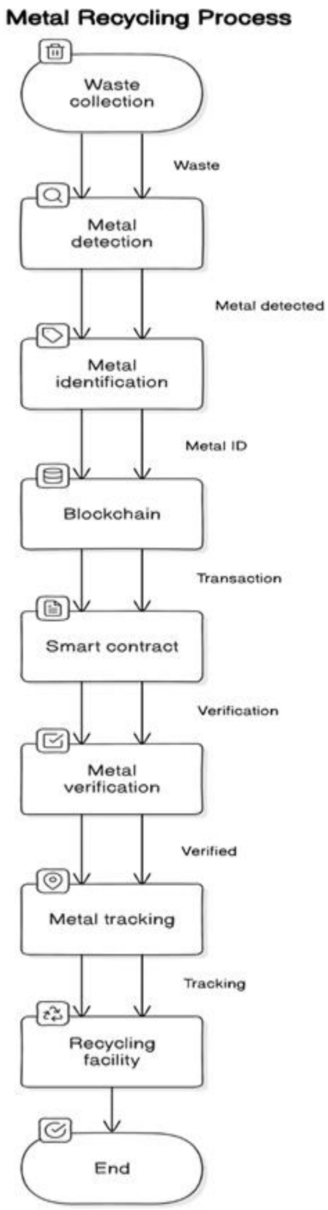

Figure 6. The metal recycling process steps in blockchain from the waste collection point toward the recycling facility.

Despite these challenges, the potential benefits of blockchain technology in the EV supply chain remain compelling. Ongoing research and collaborative efforts to address the technical, operational, and regulatory obstacles will be crucial for blockchain's widespread adoption and successful integration in this industry.

In Figure 8, a schematic is presented, which illustrates the three most possible EV battery recycling loops through which it is possible to recover metals [67,90,93]. Direct recycling aims to recover cathode materials in the most time-efficient and chemically sustainable way, but current chemical engineering limitations prevent the complete recycling of all metal parts and minerals due to hazardous materials and complex processing steps, such as smelting, which requires hydrometallurgical processing (leaching) [87,101,104,108].

In both pyro- and hydrometallurgical recycling, i.e., smelting, the cost of lithium recovery can excess realistic price whilst pyrometallurgical recycling of aluminum that remains in slag in addition to incinerated graphite offers affordable solutions [20,102,110].

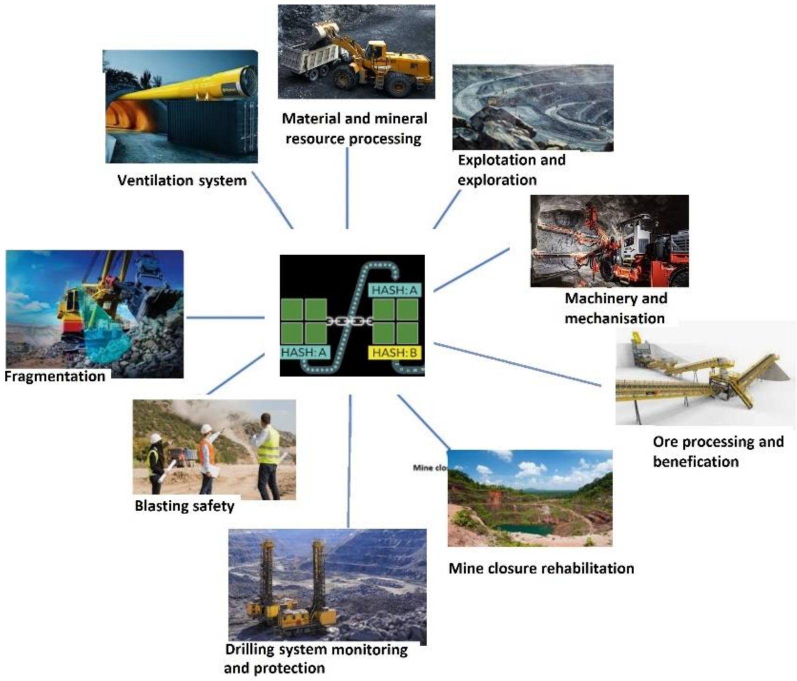

Figure 7. Schematic presentation of blocks of the main processing aspects related to safety in the mining industry and their interaction with each other in blockchain sustainability management.

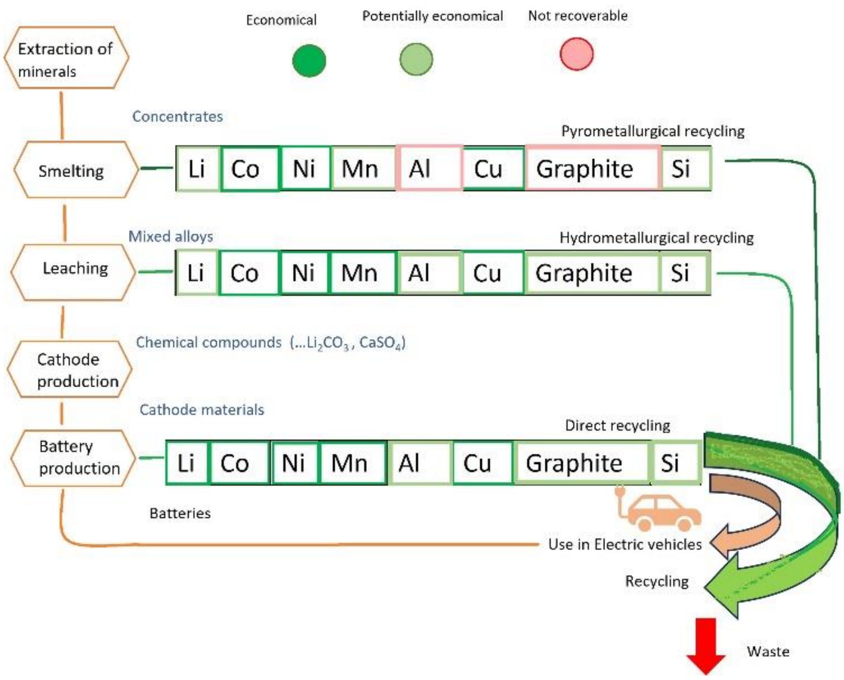

Figure 8. Schematic of three recycling scenarios close battery material loops and identify which materials are recovered. In practice, not all materials undergo every processing step [102,110].

Pyro- and hydrometallurgical recycling processes have emerged as two of the primary methods for recovering valuable materials from spent lithium-ion batteries. Pyrometallurgical recycling involves subjecting the batteries to high temperatures, often in the presence of a reducing agent, to extract metals such as cobalt and nickel. This process is relatively simple and can be carried out on an industrial scale, but it is accompanied by large amounts of CO_2 emission and often fails to recover other important components such as lithium salts and plastics [111,112]. Hydrometallurgical recycling, on the other hand, utilizes a series of chemical leaching and separation steps to extract and purify the desired metals. This approach is generally more environmentally friendly, as it does not involve the high-temperature smelting step, but it can be more complex and energy-intensive [111].

In contrast to these traditional recycling methods, innovative techniques have been developed that overcome the drawbacks of pyrometallurgical and hydrometallurgical processes of battery recycling [113–115]. One such approach is the use of biometallurgical recycling, which employs microorganisms to extract and recover metals from the battery materials selectively. This innovative process utilizes the unique capabilities of microorganisms to extract and recover valuable metals from various waste streams, including electronic waste (e-waste) and low-grade ores [116,117].

Microorganisms, specifically certain bacteria and fungi, can interact with and extract metal ions from a wide range of materials. These microorganisms can be employed in a process known as "bioleaching," where they break down the waste materials and release the metal ions into an aqueous solution, making them. This process is particularly effective in recovering metals from electronic waste, which typically contains a diverse array of critical and valuable metals, such as copper, tin, lead, and zinc, which are more accessible for recovery [116].

Another innovative technique is the use of electrochemical recycling, which leverages the electrochemical properties of the battery components to separate and recover the materials. Electrochemical recycling is a process that utilizes electrochemical techniques to extract and recover these valuable metals from spent lithium-ion batteries, reducing the need for traditionally used hazardous chemicals and energy-intensive thermal treatments [114,115]. This process involves several steps, including disassembly, electrode separation, and metal extraction. The disassembly stage involves safely removing the battery pack from the device and separating the individual cells. The electrodes are then separated from the cells, and the metals are extracted using electrochemical techniques, such as leaching and selective precipitation [114,115].

This method can be highly selective and efficient but may also require specialized equipment and a more complex process setup.

While both pyrometallurgical and hydrometallurgical recycling processes have advantages and disadvantages, developing new innovative techniques that reduce the use of chemicals, high temperatures, and secondary pollution is crucial for a sustainable and circular battery material economy.

4. Electric Vehicles in the Road to the Sustainable Economy via Blockchain

Blockchain technology can help with the global standardization issues facing the EV industry by offering a transparent and safe way to track and verify compliance across geographical boundaries, with the huge potential in real-time tracking of components, materials, and infrastructure within compliance with national and international standards [94,103,105]. Blockchain has the potential to promote transparency and unify billing mechanisms, grid interoperability, and infrastructure resilience through immutable records [5,21,102,106].

4.1. Road to Sustainable Practices in EV Production via Resource-Balanced Economy

The transition to electric mobility is not without its challenges, as creating sustained market growth while meeting highly ambitious targets requires coordinated efforts from all stakeholders, including governments, the automobile industry, electricity suppliers, and consumers [5,77,100,105,109]. In the early days of the development of EVs, many countries urged for controlled development of innovative technologies that would enable the mitigation of fossil fuel pollutant-induced climate change and initially established [117]. Governments worldwide are supporting the adoption of regulations for EVs, with the

United States aiming for 100 million profit from the industry by 2030 and California setting a target of 5 million EVs on its roads by the same year [118–120].

The Electric Vehicles Initiative (EVI) is a multi-governmental policy forum established in 2010 under the Clean Energy Ministerial (CEM) [120,121]. The primary goal of this initiative was to promote global EV adoption by addressing policy challenges and fostering knowledge-sharing among policymakers, with the Global EV Outlook monitoring progress and enabling insights for acceleration of road transport electrification [121]. The initiative is coordinated by the International Energy Agency, and its members include Canada, China, the United States, and several other countries that have been actively involved in the 2022–2023 period [118,119,121].

The linear economic model, centered on throughput and endless growth, has caused resource depletion, massive waste, and unequal wealth distribution, making implementing a circular economy essential for achieving sustainable prosperity by aligning the economy, society, and the natural environment [104,122]. Navigating the complexities of a modern economy, including EV grid integration, requires a careful balance between resource allocation and efficient resource use [103,108,122]. The transition of the EV industry to a circular economy leveraging transparency, metal recycling, and technological innovations can promote sustainable prosperity by harmonizing economic growth with societal and environmental well-being [93,101,108,123–125].

The electric vehicle industry has experienced remarkable growth in recent years, driven in part by the steady decline in lithium-ion battery prices. From 2010 to 2020, battery costs dropped by an estimated 89%, thanks to advancements in battery chemistry, increased manufacturing capacity, and improvements in energy density and charging speed [126]. This price reduction has been a key factor in the surging global demand for electric vehicles, with the market reaching new heights in 2024 with 17.1 million EVs sold worldwide, a 25 percent year-over-year increase [126,127]. Due to the various regulatory frameworks and incentives that shaped the global EV markets, such as novel subsidies, tax credits, and improved emission standards, the popularity of EVs increased worldwide, particularly in China, Europe, and North America. Regulatory frameworks such as China's trade-in scheme, Europe's emission pooling strategies, and North America's tax credits have influenced consumer and manufacturer behavior and increased demand for EV vehicles [126,127]. Following this trend, over the past two years, the prices of key battery metals, such as lithium, cobalt, and nickel, have experienced significant declines due to a combination of oversupply and fluctuating demand, particularly from the electric vehicle sector in China. Lithium hydroxide prices, for instance, have fallen nearly 75% from their peak in 2022, dropping to approximately USD 23 per kilogram by late 2023. This decline is attributed to increased global production and a slowdown in EV sales growth in China [127]. Similarly, cobalt prices have plummeted from USD 40 per pound in 2022 to about USD 11 per pound in 2024, primarily due to overproduction, especially from the Democratic Republic of Congo, and a shift in the EV industry toward batteries that require less or no cobalt. The trend in EV battery metal prices from 2022 onward is summarized in Table 2.

Table 2. Summarized recent trends in electric vehicle (EV) battery metal prices and projections up to 2025.

Battery Metal	Peak Price (2022–2023)	Current Price (2024)	Trend	Projection for 2025
Lithium (LiOH)	~USD 85/kg	~USD 23/kg	Down (75 percent due to oversupply)	Expected stabilization as mine closures reduce supply and EV demand increases
Cobalt (Co)	~USD 80/kg	~USD 24/kg	Down (Oversupply from the DRC, shift to cobalt-free batteries)	Slight recovery due to reduced mining activity
Nickel (Ni)	~USD 30,000/ton	~USD 18,000/ton	Down (High Indonesian production, slowing Chinese EV sales)	Continued downward pressure might stabilize if demand increases

4.2. Standardization and Regulations for Sustainability of EVs

Standardization is crucial for the widespread adoption and success of EVs, particularly in areas such as critical metals mining and recycling, as well as in ensuring the performance of acoustic equipment, fire retardance, and thermal management [2,9,121,125]. Standardization ensures consistent EV safety standards, reduces system failure risks, and promotes interoperability across brands and models while also applying to production technology and metal recyclability, fostering innovation and lowering adoption costs [128]. Consistent quality across electric vehicle models and brands globally is another key benefit of standardization, as it establishes benchmarks for performance, durability, and reliability [128,129]. Standardization benefits both manufacturers and producers by simplifying EV maintenance and repair, lowering production costs, improving accessibility to services, and enabling the development of a stable market that brings greater investments in research and development [2,116,128].

Governments and regulatory bodies typically mandate standards for the safety of EV and lithium batteries, and it is essential to develop regulations covering the entire manufacturing, production, and recycling lifecycle, including benefits and penalties [38,41,128,130]. To facilitate the transition to a more sustainable transportation system, it is vital to ensure the sustainability of the lithium-ion battery supply chain (LIBSC), with standardization playing a key role in establishing consistent practices across the industry. Standardization will enable global harmonization of EV technology, enabling continuous development of infrastructure and providing the feasibility and interoperability of all subsystems within the ecosystem, including mining, production, transportation, waste collection, and recycling [125,130]. Stakeholders and policymakers are introducing measures to promote the LIBSC's sustainable growth even though it is not defined yet since the electric vehicle industry is still in its preliminary stages, with relationships among its actors only beginning to form. While a growing body of literature addresses the content of sustainability assessments, limited research exists on the interactions, governance, and interfaces between supply chain stakeholders conducting these assessments. Yet, these dynamics are critical for implementing comprehensive, supply chain-wide evaluations [125,127,130].

Despite the EV industry being relatively new, it already raises concerns related to the utilization of precious metals and the production of flammable lithium-ion batteries. These issues highlight the urgent need to quickly establish safety and sustainability regulations to address potential environmental and safety risks [110,125]. Lithium battery aging is influenced by both external environmental and internal factors, with standardization playing a key role in ensuring consistent performance across various conditions [122,131,132]. External factors include the battery's location and operating environment, such as temperature, charge and discharge rate, depth of discharge (DOD), and the cut-off voltage during charging [38,41,133]. Internal factors are driven by three main mechanisms: the loss of lithium inventory (LLI), loss of active material (LAM), and conductivity loss (CL) [133]. LLI involves the formation of the solid electrolyte interphase (SEI) layer, the development of lithium dendrites, and self-discharge, while LAM includes the decomposition of cathode and anode materials and electrolyte breakdown, and CL refers to the aging process that causes the battery's current collector to degrade and the adhesive to peel off, with standardization of these factors ensuring uniformity in battery performance and lifespan across diverse applications [132,133].

Currently, Li-ion batteries remain the industry standard for electric vehicles, consumer electronics, and grid storage, with manufacturers continuing to refine their performance and cost-efficiency. However, concerns over the limited availability and uneven distribution of lithium resources have raised questions about Li-ion batteries' long-term sustainability and affordability [134,135]. The rising demand for lithium, supply chain constraints, and price volatility have prompted the development of alternative battery chemistries. Among these, sodium-ion (Na-ion) batteries have emerged as a promising contender as sodium (Na), significantly more abundant than lithium, offers a potential solution to supply constraints [134,135]. Na-ion batteries operate similarly to Li-ion batteries but use sodium-based materials instead. The widespread availability of sodium and the potential for lower production costs make Na-ion batteries particularly attractive for large-scale energy storage applications, such as electric grids and renewable energy integration. However, despite these advantages, Na-ion technology is still in the early stages of commercialization, facing challenges related to the lower energy density and shorter lifecycle compared to Li-ion batteries. As a result, while Na-ion batteries have the potential to alleviate pressure on lithium supply chains, Li-ion batteries remain the dominant choice for most applications. Continued research and development in both technologies will determine how energy storage evolves over several decades.

The circular economy should apply a closed loop between raw materials supply, recycling of used vehicles, supply chain, and waste collection, as presented in Figure 9.

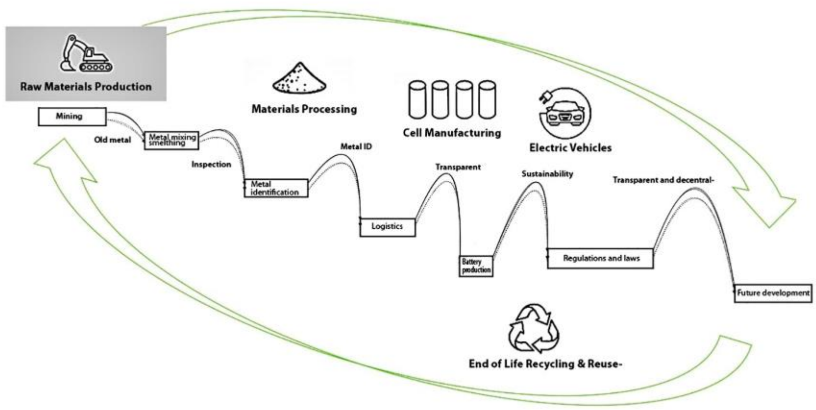

Figure 9. EV production and recycling supply chain.

As the industry evolves, implementing regulations and standardization is crucial to ensure responsible growth, minimize negative impacts, and establish minimum criteria for the safety, performance, and recycling processes of EVs [120,124]. Blockchain technology streamlines recycling by enabling efficient recovery of valuable metals, minimizing waste, and improving transparency in the recycling process.

One of the key areas where blockchain can contribute to waste reduction is in the recycling of metals. By providing a transparent and immutable record of the provenance and movement of metal materials, blockchain can help prevent the loss or misplacement of recyclable materials, ensuring that they are properly collected, processed, and reused. This can significantly reduce the amount of metal waste that ends up in landfills or incinerators, contributing to a more sustainable and circular economy.

Moreover, blockchain technology can streamline supply chain management in the metal industry, improving logistics efficiency and reducing the risk of errors or fraudulent activities [136]. By creating a shared, tamper-resistant ledger that tracks the movement of raw materials, semi-finished products, and final products, blockchain can help eliminate redundant paperwork, reduce the risk of data discrepancies, and provide real-time visibility into the supply chain.

By recording the origins, processing steps, and environmental impact of metal production, blockchain can help ensure compliance with regulations and industry standards and, at the same time, enable consumers to make informed choices about the products they purchase.

Additionally, standardization promotes global compatibility, reduces emissions, ensures safe disposal of hazardous materials, and fosters innovation by setting ambitious targets for efficiency and recyclability, driving competition and research in the industry [119,123,125]. Economic benefits of imposed regulations and standardizations include reduced manufacturing costs, market stability, and improved predictability, supported by ethical sourcing and efficient use of critical materials, which enable investors to plan long-term projects [128,130] confidently. Global resource optimization ensures the ethical and sustainable use of materials, reducing reliance on environmentally damaging mining practices, aligning with the international climate goals, and attracting environmentally focused investors who prioritize sustainability, as presented in Table 3.

Table 3. Key aspects that summarize why standardization and regulations are important for sustainable development of EVs.

	Important Aspects	Essential Features	Characteristics and Explanation
1.	Ensuring safety and performance	Consistency in quality within whole production cycle	Standardized manufacturing ensures EV components meet performance and safety standards and safe handling of hazardous materials like lithium-ion batteries to protect workers and the environment.
2.	Facilitating recycling	Materials recovery efficiency with reduction of waste	Battery design standards enable efficient disassembly and extraction of valuable metals like lithium, cobalt, and nickel.
3.	Environmental sustainability	Reducing emissions and managing hazardous materials	Regulations promote environmentally responsible EV production and ensure safe disposal or reuse of toxic substances.
4.	Global compatibility	Regional harmonization with universal production and charging infrastructure	Cross-border standardization ensures global compatibility, reducing trade barriers and infrastructure costs and simplifying recycling and repairs.
5.	Promotion of innovation	Intensified research aids in establishing new manufacturing standards	Regulations set targets for battery efficiency, recycling, and emissions, while standardization ensures fair competition and sustainability.

Table 3. *Cont.*

	Important Aspects	Essential Features	Characteristics and Explanation
6.	Economic benefits	Decrease in production costs benefits market stability	Standardized components reduce manufacturing costs, while regulations boost market stability and long-term investment in EV production and recycling.
7.	Consumer confidence	Transparency in transport and production establishes trust in the recycling process	Standardized labels and certifications inform consumers on environmental impact and safety, while regulations ensure responsible EV recycling.
8.	Critical material availability	Efficient use of scarce resources with sustainable sourcing	Recycling regulations reduce reliance on mining, while ethical sourcing prevents child labor and environmental harm.

With global standardization and regulations in the mining and production sector, blockchain can track the ethical sourcing of metals and minerals, ensuring compliance with sustainability and human rights standards [84,91,98]. Recycling streamlines processes by verifying material recovery, ensuring quality control, and certifying adherence to environmental and safety standards, thereby supporting a circular economy [87,88,93]. Extreme weather challenges in areas with harsh temperatures or adverse conditions may necessitate specialized standards for EV components like batteries and thermal management systems to ensure optimal performance and durability [132,133]. Standards should ensure that charging infrastructure is resilient to expected climate change, imposed climatic variations, and natural disasters, considering local market dynamics such as consumer preferences, incentives, and government policies. Furthermore, it should influence technology adoption by supporting cost-effective manufacturing processes and technology development to make EVs more affordable and appealing to a broader consumer base [5,83,86,134].

The main international documents relevant to EV production are presented in Table 4.

Table 4. Key major regulative documents for EV production and use.

Category	Number	Description
Safety	ISO 26262	Functional safety for automotive systems, focusing on risk management in electrical and electronic systems.
	IEC 62133	Safety requirements for portable sealed secondary cells and batteries, ensuring safe operation, handling, and protection from hazards.
	Euro NCAP/NHTSA	Vehicle crashworthiness and occupant safety standards, including specific guidelines for EVs.
Charging	IEC 62196	Specifies physical connectors and protocols for EV charging to ensure global interoperability.
	CHAdeMO, CCS, Tesla Supercharger	Charging protocols define communication between vehicles and charging stations for fast charging and compatibility.
Environmental and Emission	EU Battery Directive (2006/66/EC)	Ensures proper battery recycling and disposal to minimize environmental impact.
	U.S. EPA Energy Efficiency Standards	Regulations ensuring EVs meet energy efficiency targets to reduce overall energy consumption.

Table 4. *Cont.*

Category	Number	Description
Management Standards	ISO 9001	Quality management system standards ensure consistency and quality in manufacturing processes.
	ISO 14001	Environmental management standards to reduce ecological impact in manufacturing.
	ISO 15118	Defines communication standards between EVs and charging stations to enable smart charging and grid integration.
Performance Standards	Range and Charging Time Standards	Defines the acceptable range of vehicles on a single charge and the time required for charging.
	Thermal Management Standards	Sets guidelines for battery cooling and heating systems to maintain optimal battery performance in varying temperatures.

Global regulations and standardization create a stable, scalable, and environmentally responsible framework for the EV sector, fostering long-term investment and growth by enabling predictability, economies of scale, cross-border compatibility, reduced risks, innovation incentives, resource optimization, and environmental compliance, as schematically presented in Figure 10.

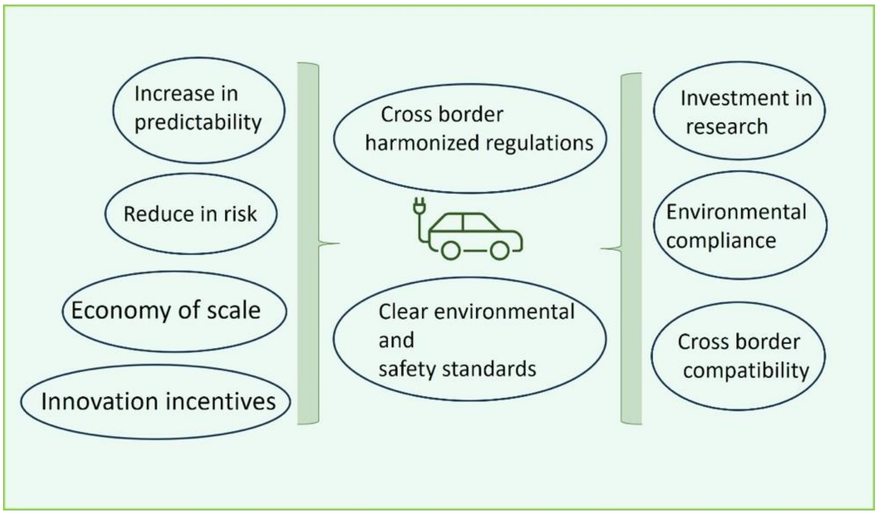

Figure 10. Schematic presentation visualizing the concepts of predictability, economies of scale, cross-border compatibility, reduced risk, innovation incentives, resource optimization, and environmental compliance.

4.3. Key Challenges in International Standardization of EVs

Unifying international standards in the EV industry faces multiple challenges, including diverse regional regulations, infrastructure variances, and grid and electricity variability [89,99,102,108,120]. Different regions have unique regulatory frameworks and safety standards, making it difficult to align international standards [2,117,121,122,125]. Additionally, charging infrastructure, such as connector standards, power levels, and communication protocols, differs across regions, and the variability in grid infrastructure, voltage levels, and renewable energy integration further complicates standardization [121,128]. Cultural and market differences, including varying consumer preferences, driving habits, and regional demands, accompanied by various industry interests and competition among global automotive manufacturers and technology providers, may lead to compromises in standardization [125,129]. Hence, the rapid evolution of technologies such as battery advancements, charging infrastructure, vehicle design, and blockchain adds complexity to harmonizing standards across regions [5,117,130]. The diversity of existing regional regulations adds to standardization obstacles due to different regional frameworks and not harmonized safety [120,128]. Additionally, infrastructure variances, such as differences in charging connector standards, power levels, and communication protocols, further complicate the establishment of a unified global standard [6,11,30,54,66]. The variability in electrical grids, voltage levels, and renewable energy integration across regions also poses a challenge, as standards must account for these regional differences [14,129,133].

The utilization of blockchain technology mitigates global standardization challenges in the EV industry by providing a secure, transparent system for tracking and verifying compliance across regions [7,10,129,131]. It enables real-time tracking of materials, components, and infrastructure, ensuring adherence to both local and international standards [14,16,21,53]. Through immutable records, blockchain fosters transparency and harmonizes charging protocols, grid compatibility, and infrastructure resilience to support faster technological advancements suitable for different markets' needs.

5. Conclusions

The transition to a sustainable, resource-balanced economy in the EV sector requires a holistic approach, integrating efficient raw material use, advanced recycling, supportive policies, and industry collaboration. Blockchain technology can enhance supply chain transparency, traceability, and responsible sourcing, supporting sustainability standards in the metal and mineral industries. However, to address resource scarcity and ensure long-term viability, solutions like material innovation, recycling improvements, and the development of alternative materials are necessary. The unification of global standards in the EV industry faces challenges due to regional regulations and infrastructure variances, but blockchain can help harmonize these standards and facilitate the adoption of electric vehicles. Ultimately, blockchain's role in ensuring compliance and transparency is key to sustainable trade and investment in the development of the EV industry.

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Abbreviations

BEVs	Battery electric vehicles
CL	Conductivity loss
DOD	Depth of discharge
EV	Electric vehicle
LAM	Loss of active material
LIBSC	Lithium-ion battery supply chain
LLI	The loss of lithium inventory
NCA	Lithium–nickel–cobalt—aluminum batteries
NCM	Lithium–nickel–cobalt–manganese batteries
OEMs	Original equipment manufacturers
PHEVs	Plug-In Hybrid Electric Vehicles

References

1. Bibra, E.M.; Connelly, E.; Dhir, S.; Drtil, M.; Henriot, P.; Hwang, I.; Le Marois, J.B.; McBain, S.; Paoli, L.; Teter, J. Global EV Outlook 2022: Securing Supplies for an Electric Future. 2022, Volume 5, p. 221. Available online: https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf (accessed on 15 March 2025).
2. Perišić, M.; Barceló, E.; Dimic-Misic, K.; Imani, M.; Spasojević Brkić, V. The role of bioeconomy in the future energy scenario: A state-of-the-art review. *Sustainability* **2022**, *14*, 560. [CrossRef]
3. Alvarenga, R.F.D.; Dewulf, J.; Guinée, J.B.; Schulze, R.; Weihed, P.; Bark, G.; Drielsma, J. Towards product-oriented sustainability in the (primary) metal supply sector. *Resour. Conserv. Recycl.* **2019**, *145*, 40–48. [CrossRef]
4. Sato, F.E.K.; Furubayashi, T.; Nakata, T. Application of energy and CO_2 reduction assessments for end-of-life vehicles recycling in Japan. *Appl. Energy* **2019**, *237*, 779–794. [CrossRef]
5. Barceló, E.; Dimić-Mišić, K.; Imani, M.; Spasojević Brkić, V.; Hummel, M.; Gane, P. Regulatory paradigm and challenge for blockchain integration of decentralized systems: Example—Renewable energy grids. *Sustainability* **2023**, *15*, 2571. [CrossRef]
6. Baars, J.; Domenech, T.; Bleischwitz, R.; Melin, H.E.; Heidrich, O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nat. Sustain.* **2021**, *4*, 71–79. [CrossRef]
7. Church, C.; Crawford, A. *Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-Carbon Economy*; International Institute for Sustainable Development: Geneva, Switzerland, 2018; pp. 279–304.
8. Pradip; Gautham, B.P.; Reddy, S.; Runkana, V. Future of mining, mineral processing and metal extraction industry. *Trans. Indian Inst. Met.* **2019**, *72*, 2159–2177. [CrossRef]
9. Kurani, K.S. The state of electric vehicle markets, 2017: Growth faces an attention gap. *Policy Brief* **2019**, *4*, 1–3. [CrossRef]
10. Mahrez, Z.; Sabir, E.; Badidi, E.; Saad, W.; Sadik, M. Smart urban mobility: When mobility systems meet smart data. *IEEE Trans. Intell. Transp. Syst.* **2021**, *23*, 6222–6239. [CrossRef]
11. Pishdad-Bozorgi, P.; Yoon, J.H.; Dass, N. Blockchain-based Information Sharing: A New Opportunity for Construction Supply Chains. *EPiC Ser. Built Environ.* **2020**, *1*, 274–282. [CrossRef]
12. Nguyen, D.; Abrantes, B.F. Blockchain Technology and the Future of Accounting and Auditing Services. In *Essentials on Dynamic Capabilities for a Contemporary World: Recent Advances and Case Studies*; Springer Nature: Cham, Switzerland, 2023; pp. 169–190.
13. Ghobakhloo, M. Industry 4.0, digitization, and opportunities for sustainability. *J. Clean. Prod.* **2020**, *252*, 119869. [CrossRef]
14. Lazarenko, Y.; Garafonova, O.; Marhasova, V.; Tkalenko, N. Digital Transformation in the Mining Sector: Exploring Global Technology Trends and Managerial Issues. *EDP Sci.* **2021**, *315*, 04006. [CrossRef]
15. Wang, S. Multi-angle Analysis of Electric Vehicles Battery Recycling and Utilization. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1011*, 012027. [CrossRef]
16. Helmers, E.; Marx, P. *Electric Cars: Technical Characteristics and Environmental Impacts*; Springer Science+Business Media: Berlin/Heidelberg, Germany, 2012; Volume 24, pp. 1–15.
17. Kiziroglou, M.E.; Boyle, D.E.; Yeatman, E.M.; Cilliers, J. Opportunities for Sensing Systems in Mining. *IEEE Trans. Ind. Inform.* **2017**, *13*, 278–286. [CrossRef]
18. Ravishankar, B.; Kulkarni, P. When Block Chain and AI Integrates. In Proceedings of the 2020 International Conference on Mainstreaming Block Chain Implementation (ICOMBI), Bengaluru, India, 21–22 February 2020; pp. 1–4.
19. Sánchez, F.; Hartlieb, P. Innovation in the Mining Industry: Technological Trends and a Case Study of the Challenges of Disruptive Innovation. *Min. Metall. Explor.* **2020**, *37*, 1385–1399. [CrossRef]
20. Barnewold, L.; Lottermoser, B.G. Identification of digital technologies and digitalisation trends in the mining industry. *Int. J. Min. Sci. Technol.* **2020**, *30*, 747–757. [CrossRef]
21. Zhang, Z.; Song, X.; Liu, L.; Yin, J.; Wang, Y.; Lan, D. Recent Advances in Blockchain and Artificial Intelligence Integration: Feasibility Analysis, Research Issues, Applications, Challenges, and Future Work. *Secur. Commun. Netw.* **2021**, *1*, 9991535. [CrossRef]
22. Filipović, D.; Trolle, A.B. The term structure of interbank risk. *J. Financ. Econ.* **2013**, *109*, 707–733. [CrossRef]
23. Vanmathi, C.; Farouk, A.; Alhammad, S.M.; Mangayarkarasi, R.; Bhattacharya, S.; Kasyapa, M.S. The Role of Blockchain in Transforming Industries Beyond Finance. *IEEE Access* **2024**, *12*, 148845–148867. [CrossRef]
24. Su, X.; Xiao, Y.; Liu, S. Analysis on the Impact of Blockchain Technology on the Accounting Profession. In Proceedings of the 7th International Conference on Economy, Management, Law and Education (EMLE 2021), Moscow, Russia, 30–31 December 2021; pp. 10–14.
25. Zhironkin, S.; Cehlár, M. Coal mining sustainable development: Economics and technological Outlook. *Energies* **2021**, *14*, 5029. [CrossRef]
26. Segura-Salazar, J.; Tavares, L.M. Sustainability in the Minerals Industry: Seeking a Consensus on Its Meaning. *Multidiscip. Digit. Publ. Inst.* **2018**, *10*, 1429. [CrossRef]

27. O'Fairchea llaigh, C. Social Equity and Large Mining Projects: Voluntary Industry Initiatives, Public Regulation and Community Development Agreements. *J. Bus. Ethics* **2014**, *132*, 91–103. [CrossRef]
28. Batterham, R. The mine of the future—Even more sustainable. *Miner. Eng.* **2017**, *107*, 2–7. [CrossRef]
29. Carvalho, F.P. Mining industry and sustainable development: Time for change. *Food Energy Secur.* **2017**, *6*, 61–77. [CrossRef]
30. Jennings, C. An integrated "Mine to Mill" automation methodology applied to Sanbrado. *Stud. Ex. Repos.* 2022. Available online: https://sear.unisq.edu.au/id/eprint/51872 (accessed on 15 March 2025).
31. Zhironkin, S.; Szurgacz, D. Mining technologies innovative development: Economic and sustainable outlook. *Energies* **2021**, *14*, 8590. [CrossRef]
32. Fortier, S.M.; Nassar, N.T.; Lederer, G.W.; Brainard, J.; Gambogi, J.; McCullough, E.A. *Draft Critical Mineral List—Summary of Methodology and Background Information—US Geological Survey Technical Input Document in Response to Secretarial Order No. 3359 (No. 2018–1021)*; US Geological Survey: Sunrise Valley Drive Reston, VA, USA, 2018.
33. Crundwell, F.K.; Du Preez, N.B.; Knights, B.D.H. Production of cobalt from copper-cobalt ores on the African Copperbelt—An overview. *Miner. Eng.* **2020**, *156*, 106450. [CrossRef]
34. Jones, P.K.; Stimming, U.; Lee, A.A. Impedance-based forecasting of lithium-ion battery performance amid uneven usage. *Nat. Commun.* **2022**, *13*, 4806. [CrossRef]
35. Scrosati, B.; Garche, J. Lithium batteries: Status, prospects and future. *J. Power Sources* **2010**, *195*, 2419–2430. [CrossRef]
36. Zubi, G.; Dufo-López, R.; Carvalho, M.; Pasaoglu, G. The lithium-ion battery: State of the art and future perspectives. *Renew. Sustain. Energy Rev.* **2018**, *89*, 292–308. [CrossRef]
37. Thatipamula, S.; Malaarachchi, C.; Alam, M.R.; Khan, M.W.; Babarao, R.; Mahmood, N. Non-aqueous rechargeable aluminum-ion batteries (RABs): Recent progress and future perspectives. *Microstructures* **2024**, *4*, N-A.2024057. [CrossRef]
38. Wang, M.; Liu, K.; Dutta, S.; Alessi, D.S.; Rinklebe, J.; Ok, Y.S.; Tsang, D.C. Recycling of lithium iron phosphate batteries: Status, technologies, challenges, and prospects. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112515. [CrossRef]
39. Young, K.; Wang, C.; Wang, L.Y.; Strunz, K. Electric vehicle battery technologies. In *Electric Vehicle Integration into Modern Power Networks*; Springer: New York, NY, USA, 2012; pp. 15–56.
40. Konarov, A.; Myung, S.T.; Sun, Y.K. Cathode materials for future electric vehicles and energy storage systems. *ACS Energy Lett.* **2017**, *2*, 703–708. [CrossRef]
41. Koech, A.K.; Mwandila, G.; Mulolani, F.; Mwaanga, P. Lithium-ion battery fundamentals and exploration of cathode materials: A review. *South Afr. J. Chem. Eng.* **2024**, *50*, 321–334. [CrossRef]
42. Bandhu, K.C.; Litoriya, R.; Lowanshi, P.; Jindal, M.; Chouhan, L.; Jain, S. Making drug supply chain secure traceable and efficient: A Blockchain and smart contract based implementation. *Multimed. Tools Appl.* **2022**, *82*, 23541–23568. [CrossRef] [PubMed]
43. Song, J.M.; Sung, J.; Park, T. Applications of Blockchain to Improve Supply Chain Traceability. *Procedia Comput. Sci.* **2019**, *162*, 119–122. [CrossRef]
44. Luyten, S.; Büscher, J.; Driesen, J.; Leemput, N.; Geth, F.; Roy, J.V. Standardization of conductive AC charging infrastructure for electric vehicles. In Proceedings of the 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, Sweden, 10–13 June 2013; pp. 1–4.
45. Kubota, K.; Dahbi, M.; Hosaka, T.; Kumakura, S.; Komaba, S. Towards K-ion and Na-ion batteries as "beyond Li-ion". *Chem. Rec.* **2018**, *18*, 459–479. [CrossRef] [PubMed]
46. Graham, J.D.; Belton, K.B.; Xia, S. How China beat the US in electric vehicle manufacturing. *Issues Sci. Technol.* **2021**, *37*, 72–79.
47. Razmjoo, A.; Ghazanfari, A.; Jahangiri, M.; Franklin, E.; Denai, M.; Marzband, M.; Maheri, A. A comprehensive study on the expansion of electric vehicles in Europe. *Appl. Sci.* **2022**, *12*, 11656. [CrossRef]
48. Alatawneh, A.; Torok, A. A predictive modeling framework for forecasting cumulative sales of euro-compliant, battery-electric and autonomous vehicles. *Decis. Anal. J.* **2024**, *11*, 100483. [CrossRef]
49. Sawicki, M.; Shaw, L.L. Advances and challenges of sodium ion batteries as post lithium ion batteries. *Rsc. Adv.* **2015**, *5*, 53129–53154. [CrossRef]
50. Yu, R.; Wang, X.; Xu, X.; Zhang, Z. Research on Forecasting Sales of Pure Electric Vehicles in China Based on the Seasonal Autoregressive Integrated Moving Average–Gray Relational Analysis–Support Vector Regression Model. *Systems* **2024**, *12*, 486. [CrossRef]
51. Wang, H.; Feng, K.; Wang, P.; Yang, Y.; Sun, L.; Yang, F.; Chen, W.Q.; Li, J. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. *Nat. Commun.* **2023**, *14*, 1246. [CrossRef] [PubMed]
52. Ou, S.; Hao, X.; Lin, Z.; Wang, H.; Bouchard, J.; He, X.; Wu, Z.; Zheng, J.; Lv, R.; LaClair, T.J. Light-duty plug-in electric vehicles in China: An overview on the market and its comparisons to the United States. *Renew. Sustain. Energy Rev.* **2019**, *112*, 747–761. [CrossRef]
53. Beaudet, A.; Larouche, F.; Amouzegar, K.; Bouchard, P.; Zaghib, K. Key challenges and opportunities for recycling electric vehicle battery materials. *Sustainability* **2020**, *12*, 5837. [CrossRef]

54. Niri, A.J.; Poelzer, G.A.; Zhang, S.E.; Rosenkranz, J.; Pettersson, M.; Ghorbani, Y. Sustainability challenges throughout the electric vehicle battery value chain. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114176. [CrossRef]
55. Holroyd, C. Corporate social responsibility, Indigenous Peoples and mining in Scandinavia. In *Local Communities and the Mining Industry*; Routledge: London, UK, 2023; pp. 103–122.
56. Yang, A.; Liu, C.; Yang, D.; Lu, C. Electric vehicle adoption in a mature market: A case study of Norway. *J. Transp. Geogr.* **2023**, *106*, 103489. [CrossRef]
57. Patil, G.; Pode, G.; Diouf, B.; Pode, R. Sustainable Decarbonization of Road Transport: Policies, Current Status, and Challenges of Electric Vehicles. *Sustainability* **2024**, *16*, 8058. [CrossRef]
58. Cazzola, P.; Paoli, L.; Teter, J. Trends in the Global Vehicle Fleet: Managing the SUV Shift and the EV Transition. 2023. Available online: https://www.globalfueleconomy.org/data-and-research/publications/trends-in-the-global-vehicle-fleet-2023 (accessed on 15 March 2025).
59. Khaleel, M.; Nassar, Y.; El-Khozondar, H.J.; Elmnifi, M.; Rajab, Z.; Yaghoubi, E.; Yaghoubi, E. Electric vehicles in China, Europe, and the United States: Current trend and market comparison. *Int. J. Electr. Eng. Sustain.* **2024**, *2*, 20.
60. Mohammadi, F.; Saif, M. A comprehensive overview of electric vehicle batteries market. *e-Prime-Adv. Electr. Eng. Electron. Energy* **2023**, *3*, 100127. [CrossRef]
61. Kok, I.; Hall, D. Battery electric and plug-in hybrid vehicle uptake in European cities. *Work. Pap.* **2023**, 1.
62. Antony Jose, S.; Dworkin, L.; Montano, S.; Noack, W.C.; Rusche, N.; Williams, D.; Menezes, P.L. Pathways to Circular Economy for Electric Vehicle Batteries. *Recycling* **2024**, *9*, 76. [CrossRef]
63. Rostovski, J.K. How a Battery and Key Metals Shortage Could Halt the Growth of the Electric Vehicle Market. In *Global Energy Transition and Sustainable Development Challenges*; Scenarios, Materials, and Technology; Springer Nature: Cham, Switzerland, 2024; Volume 2, pp. 125–140.
64. Mancini, L.; Sala, S. Social impact assessment in the mining sector: Review and comparison of indicators frameworks. *Resour. Policy* **2018**, *57*, 98–111. [CrossRef]
65. Mudd, G.M. Sustainable/responsible mining and ethical issues related to the Sustainable Development Goals. *Geol. Soc. Lond.* **2020**, *508*, 187–199. [CrossRef]
66. Leon, E.M.; Miller, S.E. An applied analysis of the recyclability of electric vehicle battery packs. *Resour. Conserv. Recycl.* **2020**, *157*, 104593. [CrossRef]
67. Luong, J.H.; Tran, C.; Ton-That, D. A paradox over electric vehicles, mining of lithium for car batteries. *Energies* **2022**, *15*, 7997. [CrossRef]
68. Nordqvist, A.; Wimmer, M.; Grynienko, M. Gravity flow research at the Kiruna sublevel caving mine during the last decade and an outlook into the future. In *MassMin 2020: Proceedings of the Eighth International Conference Exhibition on Mass Mining*; University of Chile: Santiago, Chile, 2020; pp. 505–518.
69. Yin, J.Z.; Shi, A.; Yin, H.; Li, K.; Chao, Y. Global lithium product applications, mineral resources, markets and related issues. *Nat. Sci.* **2024**, *1*, 197–217.
70. Phelps-Barber, Z.; Trench, A.; Groves, D.I. Recent pegmatite-hosted spodumene discoveries in Western Australia: Insights for lithium exploration in Australia and globally. *Appl. Earth Sci.* **2022**, *131*, 100–113. [CrossRef]
71. Schlosser, N. Externalized Costs of Electric Automobility: Social-Ecological Conflicts of Lithium Extraction in Chile (No. 144/2020). *Work. Pap.* Leibniz Information Center for Economics Working Paper. 2020. Available online: https://hdl.handle.net/10419/222406 (accessed on 15 March 2025).
72. Winjobi, O.; Kelly, J.C.; Dai, Q. Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. *Sustain. Mater. Technol.* **2022**, *32*, e00415. [CrossRef]
73. Li, Y.; Tan, Z.; Liu, Y.; Lei, C.; He, P.; Li, J.; He, Z.; Cheng, Y. Past, present and future of high-nickel materials. *Nano Energy* **2024**, *119*, 109070. [CrossRef]
74. Cheng, A.L.; Fuchs, E.R.; Karplus, V.J.; Michalek, J.J. Electric vehicle battery chemistry affects supply chain disruption vulnerabilities. *Nat. Commun.* **2024**, *15*, 2143. [CrossRef]
75. Chae, O.B.; Adiraju, V.A.; Lucht, B.L. Lithium cyano tris (2,2,2-trifluoroethyl) borate as a multifunctional electrolyte additive for high-performance lithium metal batteries. *ACS Energy Lett.* **2021**, *6*, 3851–3857. [CrossRef]
76. Clausen, E.; Sörensen, A. Required and desired: Breakthroughs for future-proofing mineral and metal extraction. *Miner. Econ.* **2022**, *35*, 521–537. [CrossRef]
77. Liu, L.; Wang, S.; Zhang, Z.; Fan, J.; Qi, W.; Chen, S. Fluoroethylene carbonate as an electrolyte additive for improving interfacial stability of high-voltage $LiNi_{0.6}Co_{0.2}M_{0.2}O_2$ cathode. *Ionics* **2019**, *25*, 1035–1043. [CrossRef]
78. Chengjian, X.; Qiang, D.; Gaines, L.; Hu, M.; Arnold, T.; Bernhard, S. Reply to: Concerns about global phosphorus demand for lithium-iron-phosphate batteries in the light electric vehicle sector. *Commun. Mater.* **2022**, *3*, 14. [CrossRef]
79. De Putter, T. "Cobalt means conflict"–Congolese cobalt, a critical element in lithium-ion batteries. *Acad. Overzeese Wet.* **2019**, *65*, 97–110.

80. Bernards, N. Child labour, cobalt and the London Metal Exchange: Fetish, fixing and the limits of financialization. *Econ. Soc.* **2021**, *50*, 542–564. [CrossRef]
81. Mitchell, C.; Deady, E. *Graphite Resources, and Their Potential to Support Battery Supply Chains, in Africa*; British Geological Survey Open Report OR/21/039; NERC: Atlanta, GA, USA, 2021; 30p.
82. Ramji, A.; Dayemo, K. *Releasing the Pressure: Understanding Upstream Graphite Value Chains and Implications for Supply Diversification*; University of California: Oakland, CA, USA, 2024. [CrossRef]
83. Guo, X.; Lu, Y.; Zhang, Q.; Ren, J.; Cai, W. The Geological Characteristics, Resource Potential, and Development Status of Manganese Deposits in Africa. *Minerals* **2024**, *14*, 1088. [CrossRef]
84. Oruko, R.O.; Edokpayi, J.N.; Msagati, T.A.; Tavengwa, N.T.; Ogola, H.J.; Ijoma, G.; Odiyo, J.O. Investigating the chromium status, heavy metal contamination, and ecological risk assessment via tannery waste disposal in sub-Saharan Africa (Kenya and South Africa). *Environ. Sci. Pollut. Res.* **2021**, *28*, 42135–42149. [CrossRef]
85. Mwitwa, J.; German, L.; Muimba-Kankolongo, A.; Puntodewo, A. Governance and sustainability challenges in landscapes shaped by mining: Mining-forestry linkages and impacts in the Copper Belt of Zambia and the DR Congo. *For. Policy Econ.* **2012**, *25*, 19–30. [CrossRef]
86. Goodenough, K.; Deady, E.; Shaw, R. *Lithium Resources, and Their Potential to Support Battery Supply Chains, in Africa*; British Geological Survey, (OR/21/037); NERC: Atlanta, GA, USA, 2021.
87. Umair, S.; Björklund, A.; Petersen, E.E. Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. *Resour. Conserv. Recycl.* **2015**, *95*, 46–57. [CrossRef]
88. Billy, R.G.; Müller, D.B. Aluminium use in passenger cars poses systemic challenges for recycling and GHG emissions. *Resour. Conserv. Recycl.* **2023**, *190*, 106827. [CrossRef]
89. Jones, B.; Elliott, R.; Nguyen-Tien, V. The EV revolution: The road ahead for critical raw materials demand. *Appl. Energy* **2020**, *280*, 115072. [CrossRef] [PubMed]
90. Zeng, A.; Wu, C.; Rasmussen, K.D.; Lee, S.; Lundhaug, M.; Müller, D.B.; Tan, J.; Keiding, J.K.; Liu, L.; Dai, T.; et al. Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nat. Commun.* **2022**, *13*, 1341. [CrossRef]
91. Poole, C.J.M.; Basu, S. Systematic Review: Occupational illness in the waste and recycling sector. *Occup. Med.* **2017**, *67*, 626–636. [CrossRef]
92. Ma, T.; Zhang, Q.; Tang, Y.; Liu, B.; Li, Y.; Wang, L. A review on the industrial chain of recycling critical metals from electric vehicle batteries: Current status, challenges, and policy recommendations. *Renew. Sustain. Energy Rev.* **2024**, *204*, 114806. [CrossRef]
93. Neumann, J.; Petranikova, M.; Meeus, M.; Gamarra, J.D.; 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*, 2102917. [CrossRef]
94. Kang, Y.; Lu, Q. Design and Implementation of Data Sharing Traceability System Based on Blockchain Smart Contract. *Sci. Program.* **2021**, *2021*, 1455814. [CrossRef]
95. Babaei, A.; Khedmati, M.; Jokar, M.R.A.; Tirkolaee, E.B. Designing an integrated blockchain-enabled supply chain network under uncertainty. *Nat. Portf.* **2023**, *13*, 3928. [CrossRef]
96. Yang, R.; Wakefield, R.; Lyu, S.; Jayasuriya, S.; Han, F.; Yi, X.; Yang, X.; Amarasinghe, G.; Chen, J. Public and private blockchain in construction business process and information integration. *Autom. Constr.* **2020**, *118*, 103276. [CrossRef]
97. Augustin, N.; Eckhardt, A.; Jong, A.W.D. Understanding decentralized autonomous organizations from the inside. *Electron. Mark.* **2023**, *33*, 38. [CrossRef]
98. Leavins, J.R.; Ramaswamy, V. Improving Internal Control Over Fixed Assets with BLOCKCHAIN. *Int. J. Bus. Manag. Stud.* **2023**, *4*. [CrossRef]
99. Buchholz, P.; Ericsson, M.; Steinbach, V. Breakthrough technologies and innovations along the mineral raw materials supply chain—Towards a sustainable and secure supply. *Miner. Econ.* **2022**, *35*, 345–347. [CrossRef]
100. Difrancesco, R.M.; Meena, P.; Kumar, G. How blockchain technology improves sustainable supply chain processes: A practical guide. *Oper. Manag. Res.* **2022**, *16*, 620–641. [CrossRef]
101. Cerrillo-Gonzalez, M.D.M.; Villen-Guzman, M.; Vereda-Alonso, C.; Rodriguez-Maroto, J.M.; Paz-Garcia, J.M. Towards sustainable lithium-ion battery recycling: Advancements in circular hydrometallurgy. *Processes* **2024**, *12*, 1485. [CrossRef]
102. Sermpinis, T.; Sermpinis, C. Traceability Decentralization in Supply Chain Management Using Blockchain Technologies. *arXiv* **2018**, arXiv:1810.09203. [CrossRef]
103. Sauer, P.C.; Seuring, S. Sustainable supply chain management for minerals. *J. Clean. Prod.* **2017**, *151*, 235–249. [CrossRef]
104. Gaustad, G.; Krystofik, M.; Bustamante, M.L.; Badami, K. Circular economy strategies for mitigating critical material supply issues. *Resour. Conserv. Recycl.* **2018**, *135*, 24–33. [CrossRef]
105. Upadhyay, A.; Mukhuty, S.; Kumar, V.; Kazançoğlu, Y. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. *J. Clean. Prod.* **2021**, *293*, 126130. [CrossRef]

106. Liu, Y.; Chen, S. Application of Blockchain Technology in Agricultural Water Rights Trade Management. *Sustainability* **2022**, *14*, 7017. [CrossRef]
107. Noudeng, V.; Quan, N.V.; Xuan, T.D. A Future Perspective on Waste Management of Lithium-Ion Batteries for Electric Vehicles in Lao PDR: Current Status and Challenges. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16169. [CrossRef]
108. Nygaard, A. The Geopolitical Risk and Strategic Uncertainty of Green Growth after the Ukraine Invasion: How the Circular Economy Can Decrease the Market Power of and Resource Dependency on Critical Minerals. *Circ. Econ. Sustain.* **2022**, *3*, 1099–1126. [CrossRef]
109. Cheng, M.; Sun, H.; Wei, G.; Zhou, G.; Zhang, X. A sustainable framework for the second-life battery ecosystem based on blockchain. *eTransportation* **2022**, *14*, 100206. [CrossRef]
110. Xu, J.; Thomas, H.R.; Francis, R.W.; Lum, K.R.; Wang, J.; Liang, B. A review of processes and technologies for the recycling of lithium-ion secondary batteries. *J. Power Sources* **2008**, *177*, 512–527. [CrossRef]
111. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **2019**, *575*, 75–86. [CrossRef] [PubMed]
112. Börner, M.F.; Frieges, M.H.; Späth, B.; Spütz, K.; Heimes, H.H.; Sauer, D.U.; Li, W. Challenges of second-life concepts for retired electric vehicle batteries. *Cell Rep. Phys. Sci.* **2022**, *3*, 101095. [CrossRef]
113. Tang, Y.-C.; Wang, J.; Chou, C.; Shen, Y.-H. Material and Waste Flow Analysis for Environmental and Economic Impact Assessment of Inorganic Acid Leaching Routes for Spent Lithium Batteries' Cathode Scraps. *Batteries* **2023**, *9*, 207. [CrossRef]
114. Patel, A.N.; Lander, L.; Ahuja, J.; Bulman, J.; Lum, J.K.H.; Pople, J.O.D.; Hales, A.; Patel, Y.; Edge, J. Lithium-ion battery second life: Pathways, challenges and outlook. *Front. Chem.* **2024**, *11*, 121358417.
115. Arya, S.; Kumar, S. Bioleaching: Urban mining option to curb the menace of E-waste challenge. *Bioengineered* **2020**, *11*, 640. [CrossRef]
116. Kar, K.; Hossain, M.A.; Roshni, A.; Hossain, M.S. Recovery and Recycling of Valuable Metals from Low-Grade Ores Using Microorganisms: A Brief Review. *Am. J. Pure Appl. Sci.* **2021**, *3*, 1–16.
117. Wang, Q.; Geng, F.; Zhang, P.; Chen, Y.; He, L.; Cheng, S. A Social Governance Scheme Based on Blockchain. *J. Phys. Conf. Ser.* **2020**, *1621*, 012103. [CrossRef]
118. Lutsey, N. Integrating electric vehicles within US and European efficiency regulations. *Int. Counc. Clean Transp.* **2017**, *6*, 1–16.
119. Peng, R.; Tang, J.H.C.G.; Yang, X.; Meng, M.; Zhang, J.; Zhuge, C. Investigating the factors influencing the electric vehicle market share: A comparative study of the European Union and United States. *Appl. Energy* **2024**, *355*, 122327. [CrossRef]
120. Sathiyan, S.P.; Pratap, C.B.; Stonier, A.A.; Peter, G.; Sherine, A.; Praghash, K.; Ganji, V. Comprehensive assessment of electric vehicle development, deployment, and policy initiatives to reduce GHG emissions: Opportunities and challenges. *IEEE Access* **2022**, *10*, 53614–53639. [CrossRef]
121. Florini, A. The International Energy Agency in global energy governance. *Glob. Policy* **2011**, *2*, 40–50. [CrossRef]
122. Das, H.S.; Rahman, M.M.; Li, S.; Tan, C.W. Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109618. [CrossRef]
123. Sanguesa, J.A.; Torres-Sanz, V.; Garrido, P.; Martinez, F.J.; Marquez-Barja, J.M. A review on electric vehicles: Technologies and challenges. *Smart Cities* **2021**, *4*, 372–404. [CrossRef]
124. Bacchetta, A.V.B.; Krümpel, V.; Cullen, E. Transparency with Blockchain and Physical Tracking Technologies: Enabling Traceability in Raw Material Supply Chains. *Mater. Proc.* **2021**, *5*, 1. [CrossRef]
125. Green, J.M.; Hartman, B.; Glowacki, P.F. A system-based view of the standards and certification landscape for electric vehicles. *World Electr. Veh. J.* **2016**, *8*, 564–575. [CrossRef]
126. Gillingham, K.T.; Ovaere, M.; Weber, S.M. Carbon policy and the emissions implications of electric vehicles. *J. Assoc. Environ. Resour. Econ.* **2025**, *12*, 313–352. [CrossRef]
127. Coffin, D.; Croty, P.; Walling, J.; Yuan, W.J. *The Impact of Changes in Trade Policies on the Electric Vehicle (EV) Sector: A CGE Analysis*; US International Trade Commission: Washington, DC, USA, 2024.
128. Brown, S.P.A.; Pyke, D.F.; Steenhof, P.A. Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy* **2010**, *38*, 3797–3806. [CrossRef]
129. Franzò, 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. [CrossRef]
130. Saleem, U.; Joshi, B.; Bandyopadhyay, S. Hydrometallurgical Routes to Close the Loop of Electric Vehicle (EV) Lithium-Ion Batteries (LIBs) Value Chain: A Review. *J. Sustain. Metall.* **2023**, *9*, 950–971. [CrossRef]
131. Kumar, S.; Lim, W.M.; Sivarajah, U.; Kaur, J. Artificial Intelligence and Blockchain Integration in Business: Trends from a Bibliometric-Content Analysis. *Inf. Syst. Front.* **2022**, *25*, 871–896. [CrossRef] [PubMed]
132. Tian, H.; Qin, P.; Li, K.; Zhao, Z. A review of the state of health for lithium-ion batteries: Research status and suggestions. *J. Clean. Prod.* **2021**, *261*, 120813. [CrossRef]

133. Kumar, G.; Mikkili, S. Advancements in EV international standards: Charging, safety and grid integration with challenges and impacts. *Int. J. Green Energy* **2024**, *21*, 2672–2698. [CrossRef]
134. Chayambuka, K.; Mulder, G.; Danilov, D.L.; Notten, P.H.L. From Li-Ion Batteries toward Na-Ion Chemistries: Challenges and Opportunities. *Adv. Energy Mater.* **2020**, *10*, 2001310. [CrossRef]
135. Haddad, A.Z.; Hackl, L.; Aküzüm, B.; Pohlman, G.; Magnan, J.F.; Kostecki, R. How to make lithium extraction cleaner, faster and cheaper—In six steps. *Nature* **2023**, *616*, 245. [CrossRef]
136. Balcıoğlu, Y.S.; Çelik, A.A.; Altındağ, E. Integrating Blockchain Technology in Supply Chain Management: A Bibliometric Analysis of Theme Extraction via Text Mining. *Sustainability* **2024**, *16*, 10032. [CrossRef]