Review

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

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Review

Recycling or Sustainability: The Road of Electric Vehicles Towards 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 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 prediction of the magnitude of the future demand for EV battery guides 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, 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 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.

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1. Introduction

As the global shift towards 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 green-house gas emissions and other forms of environmental degradation [2,3]. Standardized manufacturing guarantees that electric vehicles (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

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addressing climate change, electric car revolution has a potential to provide negative impact on sustain-able mining and 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 development in blockchain technology and its application across all industries and economy, can bring positive impact on these developments [5,10]. Hereby in addressing critical aspects of electric vehicles development, block-chain technology has 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 environ-mentally 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 give answer to the following questions:

(i) What are the crucial issues in the ongoing debate on the development of 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 sustain-ability trends?

(iv) How prediction of the magnitude of the future demand for EV batteries guides 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 EV industry.

It is structured as follows:

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

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 of electric vehicles and trends in 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 produce electric vehicles.

2.1. Towards Industry 4.0 and Beyond

Modern industry stands at the cusp of a new era, referred 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

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sustainability [10,13]. In the mining sector, demand for EV drove towards urge for deeper mining coupled with the need to optimize these operations under the constraints of the Paris Agreement, 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 intro-duction 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 those novel industry and high difficulty in implementing these transformative technologies across the sector [22–24].

As the mining industry navigates this transition towards a new era of EV , 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].

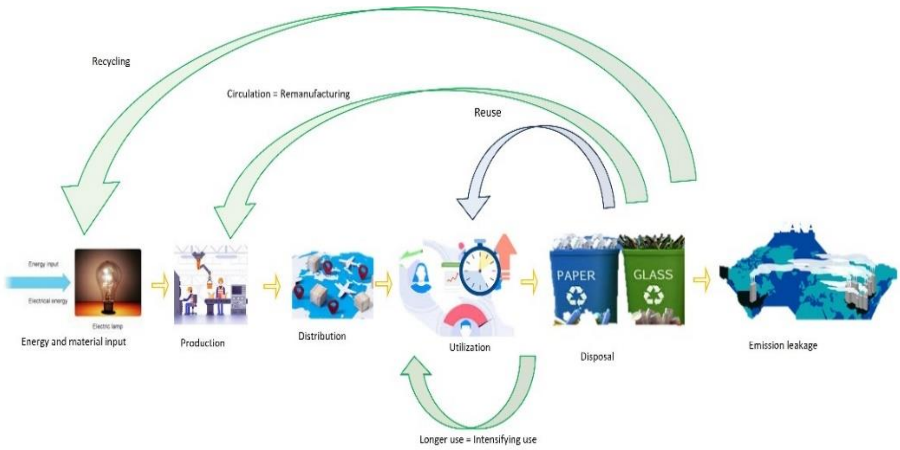

Figure 1. Schematic presentation of modern mining industry providing energy driven materials. .

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 with are NCA (Li-NiCoAl oxide), NMC (Li-NiMnCo oxide), 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 the requirement for transparency and stronger environmental, social and governance (ESG) compliance regulations [27,32,35,37].

2.3. The Rise of EV: 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 EV industry is emerging in Europe as a highly dynamic bringing new markets and key producers, creating competitiveness on global scale in electric car market that brings continuously development of more affordable models [45,47]. Nowadays China still dominates production and sales of EV on a global market with Europe reaching significant lead in total car sales, large share of existing car inventories [47,48]. 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].

The China`s strategic approach to driving the adoption of EVs has been a subject of significant interest and analysis with the electric vehicle sales experienced a remark-able increase in 2022, with battery electric vehicle (BEV) sales growing by 60% compared to 2021, reaching 4.4 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 promising products such as fully electric fleets, cheaper cars, greater investment integrating vertically with mining industry to enable cheap, fast and sustainable key minerals for battery-making [48,50]. This situation enables global consumers to choose within various options of ever-increasing electric car models that reached 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 towards 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 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

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automotive manufacturers across different regions suggests a trend towards SUVs for both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), with regional variations in battery chemistry choices [55–57].

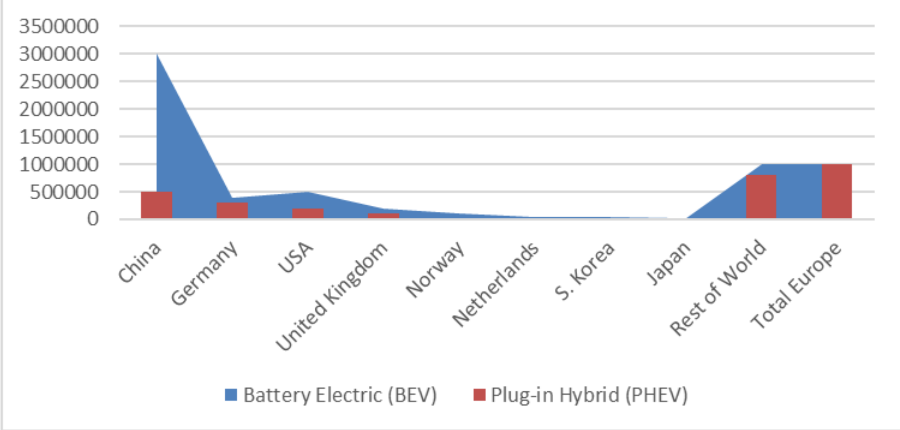

Figure 2. Battery electric and plug-in hybrid vehicle sales across markets in 2023. Modified from [58,59].

The shift towards 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 de-pends 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 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 Colt 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 US (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 in 41% in China, 44% in South Korea, 29% in Japan, 95% in the US, 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]. There is also considerable uncertainty in the Co and Ni supply both at raw and refined material stages, which resulted in vulnerability index calculation along the supply chain [71,73].

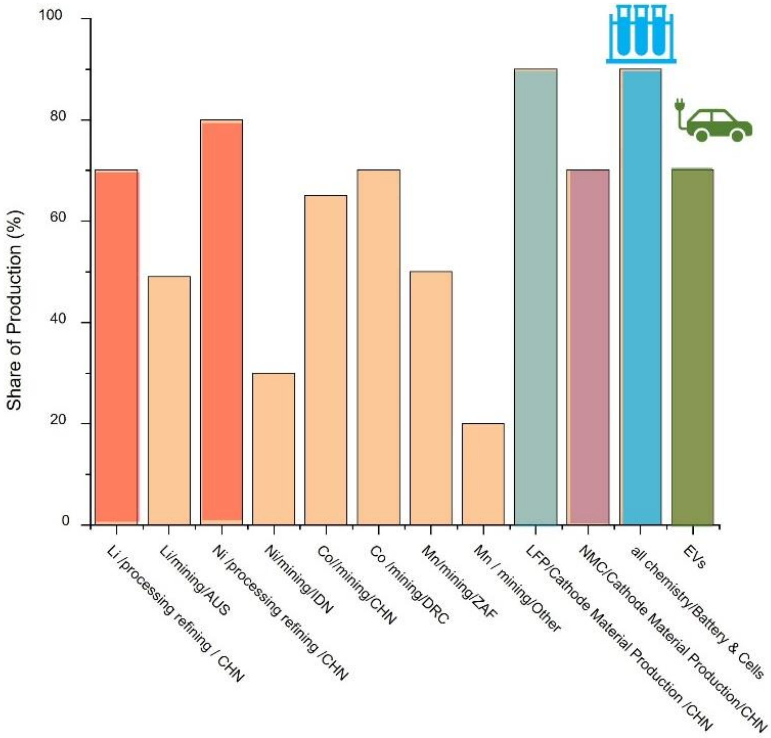

Figure 3. Distribution of EV Battery and Material Supply. Modified from [73].

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 which will continue domination of Li-NiCoMn oxide (NMC) batteries, and increase demand for over 20 times for Li, in range 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 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).

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	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	Anode is graphite with silicon to enhance performance.
	Li-S	Li-S battery	Cathode of Li and S.
	Li-	Air lithium-air battery	Lithium used as the anode and Oxygen from the air as the cathode material.

The material requirements for batteries in 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 result of the growth of the EV fleet and the required battery [9,71,72]. It's 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 BEVs, 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 beside 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].

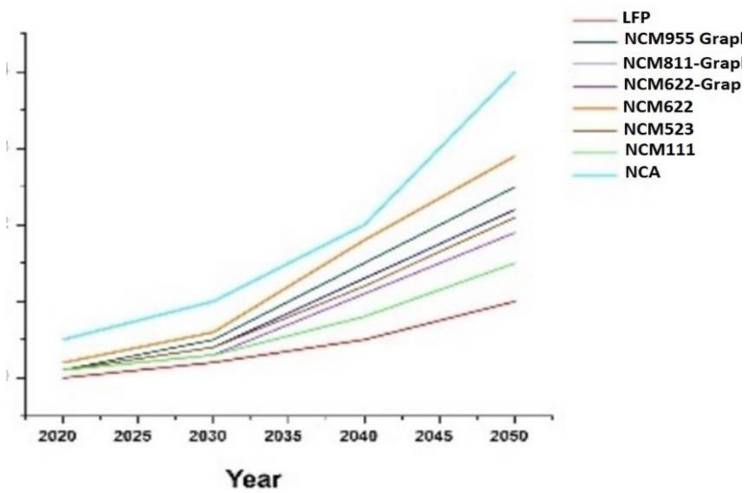

Figure 4. Battery market shares and yearly EV battery sales until 2050 for the fleet development in the STEP scenario, modified from results obtained from references [72,75].

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 a currently global powerhouse in the pro-duction and supply of critical minerals essential for the manufacturing of EVs and their battery systems [32,64,75]. 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 largest reserves found in South Africa, accounting for almost 44% of glob-al 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 and 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 a $300 billion (about $920 per person in the US) by 2050, the supply of these critical minerals from Africa will be crucial to sup-port 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]. 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

The 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]. Cryptography ensures the security and confidentiality of information in many industries and it is significant in mining as it address integrity, non-repudiation, and authentication in data sharing [18,20,94]. 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 integrity of data and any change occurring in the block alters its hash, thus ensuring secure, traceable, and immutable records in the blockchain [5,20,21].

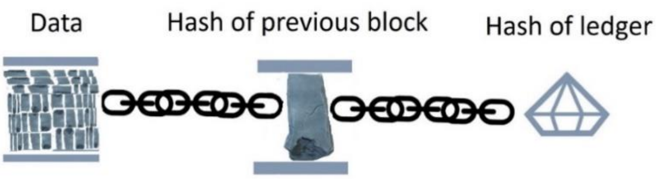

Figure 5. Schematic presentation of traceable hash elements within distributed ledger within block chain.

Control and decision-making transition from an individual or group to the whole network of participant in the blockchain is referred to as decentralization [5,94,96]. The need for the decentralized system in blockchain has been developed to overcome vulnerabilities of a traditional, centralized traditional fund transfer system in which bank as a central authority controls the entire transaction process [18,21,97]. To ad-dress such limitations, the idea of a decentralized system is introduced in which data has been utilized to store, record and synchronize transactions at separate places bringing better clarity and improving trust within the stakeholders whilst simultaneously deters participants from applying authority and control over other members of the blockchain network [97,98].

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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 potential for transformative improvements in sustainability and transparency in metal mining and recycling industries enabling sustainable practices and reducing potential conflicts [5,20,99,100].

When incorporating used metal mixtures into new vehicles, it is crucial to verify the authenticity and composition of these materials and only with used of blockchain technology it is possible to ensure verification of origin and authenticity of metals used in electric vehicle production [14,17,25,99]. By providing a secure, transparent ledger, blockchain records the provenance, composition, and quality of metal mixtures, preventing the use of counterfeit or substandard materials [14,93]. 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 track items from store to store using verified identities for online banking, ecommerce, and others [24,99,100]. Other applications are e-voting and remote participations of forum where critical decisions are made, health records for more control of data which can improve on health status, copyright protection, decentralized finance to recreate traditional finance system such as loan and insurance applications [5,23,101]. For successful technological development apart from maintaining and safeguarding corporate and personal information it is also important to motivate employees by in their daily duties and in this context blockchain appears as quicker, more effective solution for employer-employee relationship with management of system that contains all credentials of job prospects [23,103–106]. Such operations are time and money-wise sustainable solutions, checking on job candidates' training, credentials, work history, or talents [5,13,94,104]. Furthermore, they simplify complex international payroll transmission enabling more efficiently and timely cross-border payments to multinational employees, improving working conditions [11,19,42].

Integrating blockchain technology can significantly enhance the sustainability and transparency of the electric car industry[102,107]. The production of electric vehicles requires significant amount of metals, such as Li, Co and REE, 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 [39,43,93].

In transportation of metal and EV synchronized nature of blockchain informs global eco-system and opens possibility for faster agreement if there exist changes in trade chain such as a shipping route or timetable [5,17,53,95]. This synchronization simplifies resolution of problems and provides solutions, enabling precise data management within the blockchain and 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 [10,66,92,97].

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 [18,92,98,107]. 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 [10,13,18,94].

3.1. Blockchain in Metals Recycling

In the sustainable organized recycling metal center inputs and corresponding outputs are continually updated through 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

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[21,26,108]. This allows regulators and end users to verify data as the luck of connectivity between participants outside of institutional system is a key challenge. Proposed system of metal recycling blockchain system, from waste collection towards recycling facility is presented schematically with diagram shown in Figure 6.

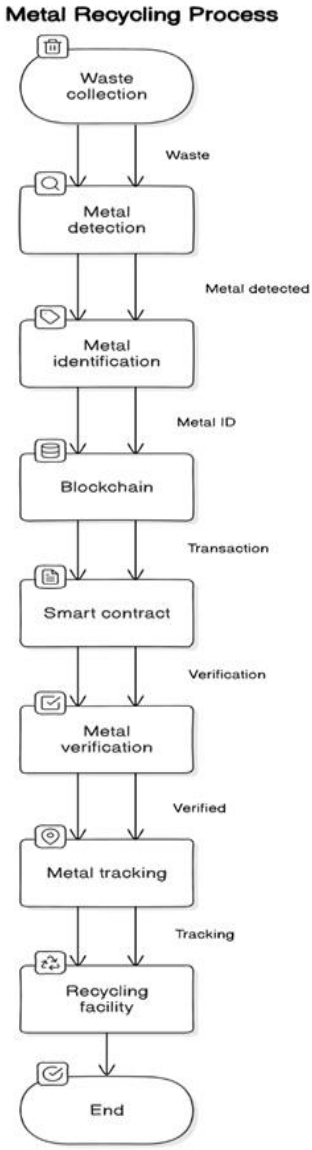

Figure 6. Metal recycling process steps in blockchain from waste collection point towards recycling facility.

Utilization of blockchain through the whole supply system, from mining industry through production of EV and recycling of metals is solution which addresses a major concern inherent in modern supply chain (SC), that they are designed as standalone and discrete systems that fail to connect actors outside SC institutions [103,106,107]. Recycling EV batteries is crucial for recovering valuable metals like Li, Co, N, and Cu, creating a sustainable supply chain and reducing dependency on limited natural reserves. Recycling of EV batteries minimizes the environmental impact of battery disposal, preventing toxic materials from polluting ecosystems whilst supporting of a circular economy by reintroducing recovered materials into production, promoting sustainability in the EV industry [1,6,52,65,96]. Therefore, blockchain offers solutions for the control of various aspects related to processing of ores and machinery in mining industry, as visually presented in Figure 7.

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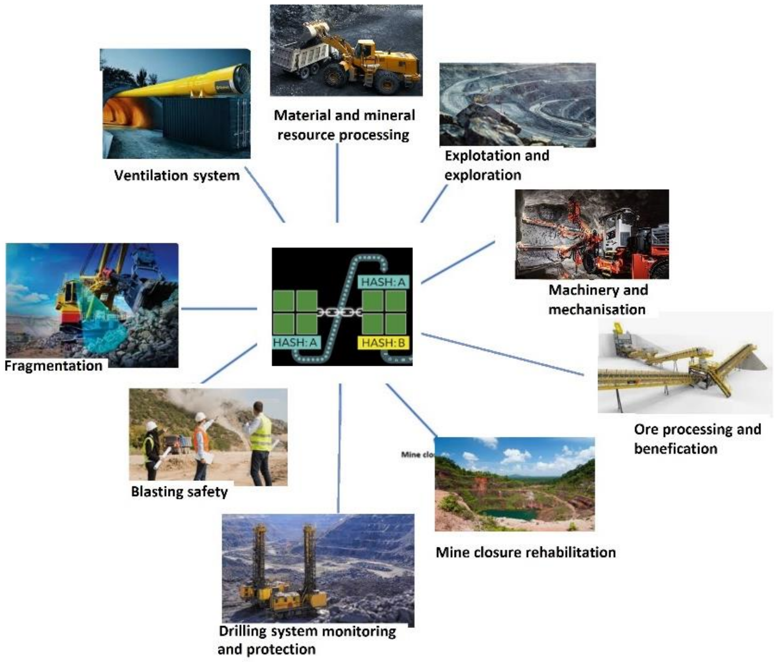

Figure 7. Schematic presentation of blocks of the main processing aspects related to safety in mining industry and their interaction with each other in the blockchain sustainability management.

In Figure 8. is presented schematic which illustrates three most possible EV battery recycling loops, through which it is possible to recover metals [66,89,92]. 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) [86,100,103,107]

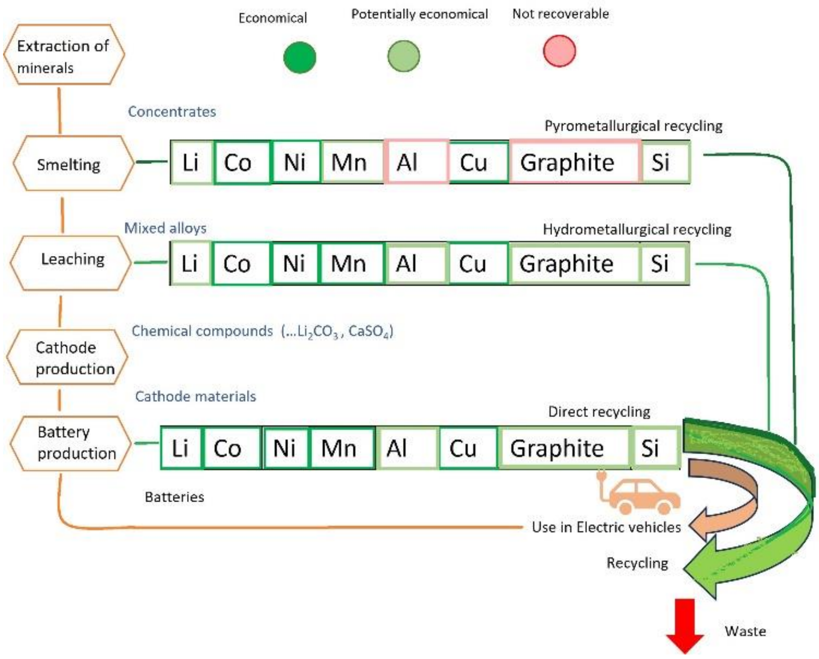

Figure 8. Schematic of three recycling scenarios close battery material loops and identify which materials are recovered. In practice, not all materials undergo every processing step. [101,109].

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In both pyro- and hydrometallurgical recycling i.e. smelting, cost of lithium recovery can excess realistic price in addition to pyrometallurgical recycling of aluminum that remains in the slag and incinerated graphite [20,101,109].

4. Electric Vehicles in Road to Sustainable Economy via Blockchain

The 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 [93,102,104]. Blockchain has the potential to promote transparency and unify billing mechanisms, grid interoperability, and infrastructure resilience through immutable records [5,21,101,105].

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 with meeting highly ambitious targets requires coordinated efforts from all stakeholders, including governments, the automobile industry, electricity suppliers, and consumers [5,76,99,104,108]. In the early days of development of EV many countries recognized urged for controlled development of innovative technologies that will enable mitigation of fossil used pollutant induced climate change and initially was established [110]. Governments worldwide are supporting adoption of regulations for EV with the United States aiming for 100 million profit from industry by 2030 and California setting a target of 5 million EVs on its roads by the same year [111,112]. The EV Initiative is a multi-governmental policy forum established in 2010 under the Clean Energy Ministerial [113,114]. 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 with enabling insights for acceleration of road transport electrification [114]. The initiative is coordinated by the International Energy Agency [111,112,114].

The linear economic model, centered on throughput and endless growth, has caused resource depletion, massive waste, and unequal wealth distribution, making the implementation of a circular economy essential for achieving sustainable prosperity by aligning the economy, society, and the natural environment [104,115]. Navigating the complexities of a modern economy, including EV grid integration, requires a careful balance between resource allocation and efficient resource use [102,107,116]. Transition of 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 [92,100,107,117].

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 [2,9,114,118]. 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. [119]. Consistent quality across electric vehicle models and brands globally is another key benefit of standardization, as it establishes bench-marks for performance, durability, and reliability [119,120]. Standardization benefits both manufacturers and producers by simplifying EV maintenance and repair, lowering production costs, improving accessibility to services, and enabling development of a stable market that brings greater investments in the research and development [2,115,118] .

Governments and regulatory bodies typically mandate standards for safety of EV and lithium batteries, and it is essential to develop regulations that cover the entire manufacturing, production, and recycling lifecycle, including both benefits and penalties [38,41,119,121]. To facilitate the transition to a more sustainable transportation system, it is vital to ensure the sustainability of the

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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, with enabling continuous development of infrastructure and providing the feasibility and interoperability of all subsystems within the overall ecosystem including mining, production, transportation, waste collection and recycling [118,122]. Stake-holders and policymakers are introducing measures to promote the LIBSC's sustain-able growth even though it is not defined yet since electric vehicle industry is still in its preliminary stages, with relationships among its actors are 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 be-tween supply chain stakeholders conducting these assessments, yet these dynamics are critical for implementing comprehensive, supply chain-wide evaluations [118,122].

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 [109,118]. 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 [115,123]. 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 [38,41,123]. Internal factors are driven by three main mechanisms: the loss of lithium inventory (LLI), loss of active material (LAM), and conductivity loss (CL) [124]. 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 [123,124].

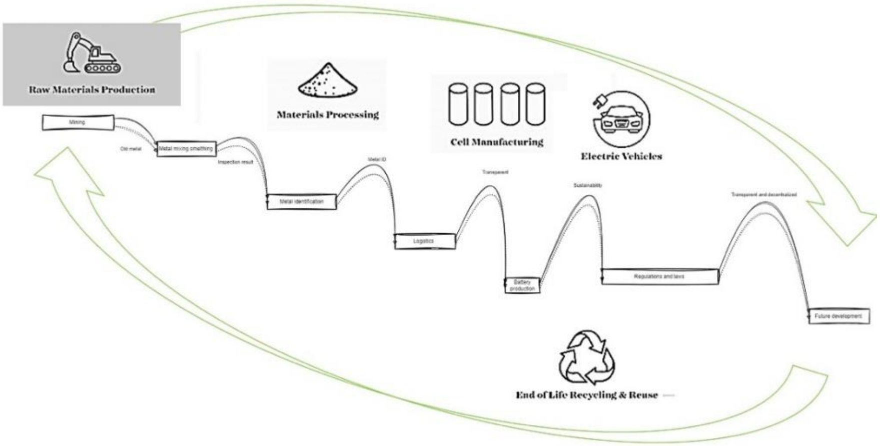

Figure 9. EVs production and recycling supply chain.

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 [114,118].

Blockchain technology streamlines recycling by enabling efficient recovery of valuable metals, minimizing waste, and improving transparency in the recycling process. 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 [113,117,119]. Economic benefits of imposed regulations and standardizations include reduced manufacturing costs, market stability, and improved predictability, supported by the ethical sourcing and efficient use of critical materials,

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which enable investors to confidently plan long-term projects [120,122]. Global resource optimization ensures the ethical and sustainable use of materials, reducing reliance on environmentally damaging mining practices, aligning with the international cli-mate goals, attracting environmentally focused investors who prioritize sustainability as presented in detail in Table 2.

Table 2. Key aspects that summarize why standardization and regulations are important for sustainable development of EV.

	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, safe handling of hazardous materials like lithium-ion batteries to pro-tect workers and the environment.
2.	Facilitating re-cycling	Materials recovery efficiency with reduc-tion 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 hazar-dous materials	Regulations promote environmentally responsib-le EV production and ensure safe disposal or reuse of toxic substances.
4.	Global compati-bility	Regional harmoniza-tion with universal production and charging infra-structure.	Cross-border standardization ensures glo-bal compatibility, reducing trade barriers, 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

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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 the 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 [83,90,97]. Recycling streamline processes should verify material recovery, ensure quality control, and certify adherence to environmental and safety standards, thereby supporting a circular economy [86,87,92]. 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 [123,124]. Standards should ensure that charging infrastructure responds to expected climate change 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 for a broader consumer base [5,82,85,125].

The main international documents relevant to EV production are presented in Table 3.

Table 3. 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.

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	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.
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.

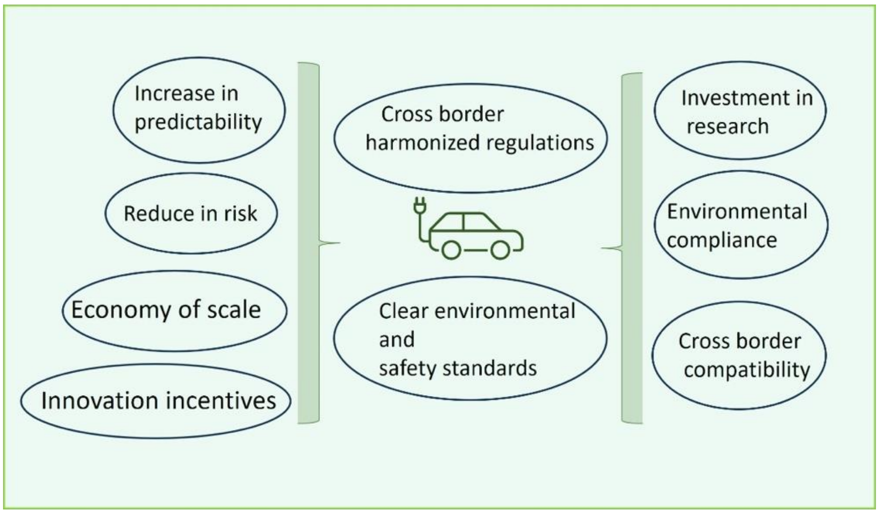

Figure 10. Schematic presentation visualizing the concepts of predictability, economies of scale, cross-border compatibility, reduced risk, innovation incentives, resource optimization, and environmental compliance.

4.3. Key Challenges in International Standardization of EVs

The unification of international standards in the EV industry faces multiple challenges, including diverse regional regulations, infrastructure variances, and grid and electricity variability[88,98,101,107,113]. Different regions have unique regulatory frameworks and safety standards, making it difficult to align international standards [2,110,115,118]. 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 [114,119]. 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[118,120]. Hence, the rapid evolution of technologies such as battery advancements, charging infrastructure, vehicle design, and blockchain adds complexity to harmonizing standards across regions [5,110,121]. The diversity of existing regional regulations adds to standardization obstacles due to different regional frameworks and not harmonized safety [113,119]. Additionally, infrastructure variances, such as differences in charging connector standards, power levels, and communication protocols, further complicate the establishment of a unified global standard [6,11,30,54,65]. 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 [14,120,124].

Utilization of blockchain technology mitigate global standardization challenges in the EV industry by providing a secure, transparent system for tracking and verifying compliance across regions [7,10,120,122]. 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 in support of faster technological advancements, suitable for different market’s needs.

5. Conclusion

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 sustain-ability standards in the metal and mineral industries. However, to address resource scarcity and ensure long-term viability, solutions like material innovation, recycling improvements, and development of alternative materials are necessary. The

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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 development of the EV industry.

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Abbreviations

EV	Electric vehicle
BEVs	Battery Electric Vehicles
PHEVs	Plug-In Hybrid Electric Vehicles
OEMs	Original Equipment Manufacturers
NCA	Lithium Nickel Cobalt Aluminum Batteries
NCM	Lithium Nickel Cobalt Manganese Batteries
LIBSC	Lithium-Ion Battery Supply Chain
DOD	Depth Of Discharge
LLI	The Loss Of Lithium Inventory
LAM	Loss Of Active Material
CL	Conductivity Loss

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