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Review

Electric Vehicle Battery Supply Chain and Critical Materials: A Brief Survey of State of the Art

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Abstract: Electric vehicles (EVs) have been garnering wide attention over conventional fossil fuel-based vehicles due to the serious concerns of environmental pollution and crude oil depletion. In this article, we have conducted a systematic literature survey to explore the battery raw material supply chain, material processing, and the economy behind the commodity price appreciation. We present significant areas of concern, including resource reserves, supply, demand, geographical distribution, battery reuse, and recycling industries. Furthermore, details of the battery supply chain and its associated steps are illustrated. The authors believe the presented study will be an information cornerstone in boosting manufacturing and understanding the key components and materials required to facilitate EV battery production. Further, this study discusses the major industries, and their policies and global market share in each material category.

Keywords: battery; electric vehicle; lithium ion; nickel chemistry; supply chain

Citation: Barman, P.; Dutta, L.; Azzopardi, B. Electric Vehicle Battery Supply Chain and Critical Materials: A Brief Survey of State of the Art. *Energies* **2023**, *16*, 3369. https://doi.org/10.3390/en16083369

Academic Editor: Javier Contreras

Received: 26 March 2023
Revised: 6 April 2023
Accepted: 9 April 2023
Published: 11 April 2023

1. Introduction

In recent years, the demand for electric vehicles (EVs) has accelerated to fulfill worldwide demands of an eco-friendly transportation system [1,2]. EV sales in 2021 surpassed more than fourfold compared to their market share in 2019. China is the global leader in EV sales, followed by Europe and the USA. China tripled its sales by 2020 [3]; Europe increased its EV sales to 2.3 million by 2021 [4]; and the USA contributed about 10% of EV sales globally until the end of 2021. Going forward, as per the industry's estimation, 7% of the global automotive industry will be EVs by 2030, which is currently only 0.2%. In the Indian subcontinent, the ambition to deploy mass numbers of EV-2-wheelers, auto-rickshaws, 4-wheelers, and buses is notable [5]. The transition of the transportation sector from engines powered by fossil fuels to battery-powered systems will reduce greenhouse gas emissions by reducing the carbon footprint [6,7]. However, specific inherent challenges associated with mining and sourcing raw materials for batteries must be resolved as they restrict their manufacturing to fulfill the ever-rising demand for EV batteries. At present, the demand and supply chain are yet to evolve to maintain a sustainable flow of raw materials to battery manufacturers.

Lead-acid, nickel-metal hydride (NiMH), and most versatile lithium-ion batteries (LBs) are among the existing battery types that have demonstrated their superiority in EVs [8–10]. In addition, several alternate battery technologies such as metal-air, sodium-ion, etc., have evolved; however, they are yet to reach their full potential [11,12]. Initially, NiMH batteries were preferred for HEVs, nevertheless, due to the superior performance demonstrated by LBs over other technologies; they are expected to replace the existing NiMH-based EVs [13].

Since BEVs and PHEVs will control the majority of the EV market, LBs will probably be a significant component of the future generation of EVs [14,15].

LBs were first intended to power portable consumer gadgets such as computers, cameras, power banks, cell phones, and other similar devices. Nonetheless, they have emerged as the top choice in a wide range of applications because of their superior quality attributes and promising performance, such as high-power density, longevity, and reduced memory effect [16–19]. This prompted a substantial boosting of battery production to meet the market's need in the past decade. Consequently, the consumption of LBs escalated more than forty folds, from 11 GWh in 2015 to 460 GWh in 2023. By the end of 2025, the total LB capacity is anticipated to exceed 800 GWh [20]. The utilization of LBs in EVs and HEVs started from 2010 onwards, diminishing the market share of NiMH [21]. On a global scale, the use of LBs in EVs has outpaced other technologies with a market share of 51%. LBs in light- and heavy-duty vehicles are predicted to expand significantly over the next ten years, reaching a startling share of 77% in 2030. Records reveal that a significant number of LBs were sold on the Chinese market over the past ten years, constituting 49% of global sales in 2019, preceded by Europe and the USA. The major breakthroughs in LBs and its related technologies are elaborated in Figure 1.

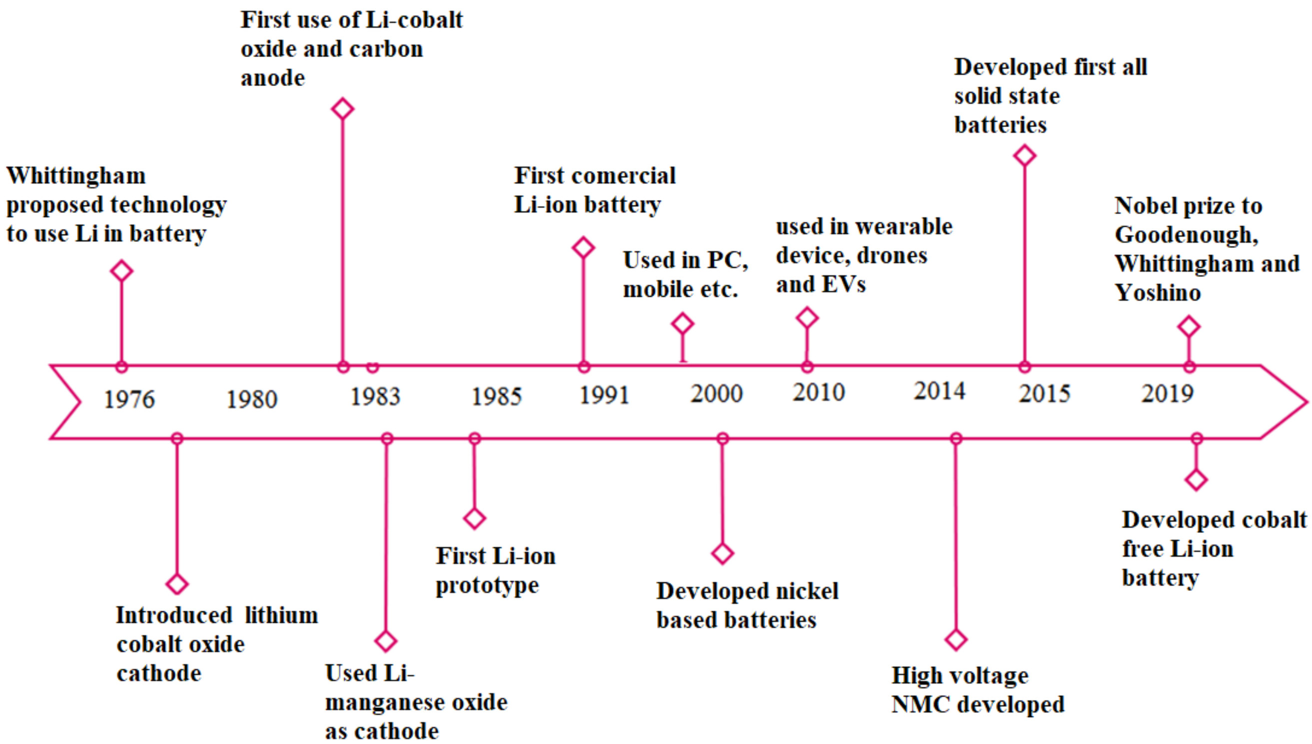

Figure 1. Major breakthroughs in LBs and its related technologies.

Industry experts have estimated that the initial cost of an EV will be equivalent to that of an ICEV by 2025. This can dramatically transform EV adoption in the near future. Furthermore, the total cost per kilometer of an EV has a favorable economics for better utilization. Presently the cost of batteries accounts for approximately one-third of the entire expense of an EV. However, the price of battery packs fell by more than 70% over the last six years. Continuous research and innovation in battery technology accompanied by an increased production scale drive the consistent decline of battery prices. As per the survey, battery prices could fall to 73 USD/kWh by 2030 as compared to today's 240 USD/kWh. Battery prices may fall even faster than this projection if the ambitions of developed countries such as France, the UK, Norway, or China are to replace ICEVs with EVs completely. Considering the global EV deployment statistics, the global demand for EV batteries could be fulfilled by at least 30 giga-factories by 2030 [3]. It requires an investment of more than 120 billion dollars solely for battery manufacturing. As per the scale of the Tesla giga-factory, it has a total manufacturing capacity of 35 GWh yearly [4].

The current demand for LBs is more than 350 GWh which is more than two times the demand in 2020. The surge in battery demand is proportional to the number of newly registered electric cars. A BEV requires an average of a 55kWh battery capacity, and a PHEV requires a 14kWh capacity. The capacity needed for medium and heavy-duty vehicles is usually larger than light-duty vehicles. The average battery capacity differs in various countries. China is the leading EV battery consumer with a market requirement of 200 GWh in 2021. Furthermore, battery demands in Europe increased by 70% in the last six years. The USA has also seen impressive demand growth that doubled in 2021. The primary reason behind this rapid demand is the capacity expansion of the battery industry. The global demand for batteries in Light Duty Electric Vehicles (LDEVs) with a comparison of leading battery manufacturing nations is represented in Figure 2 [22]. It can be seen that China is leading in the battery demand for LDEVs followed by Europe and the USA.

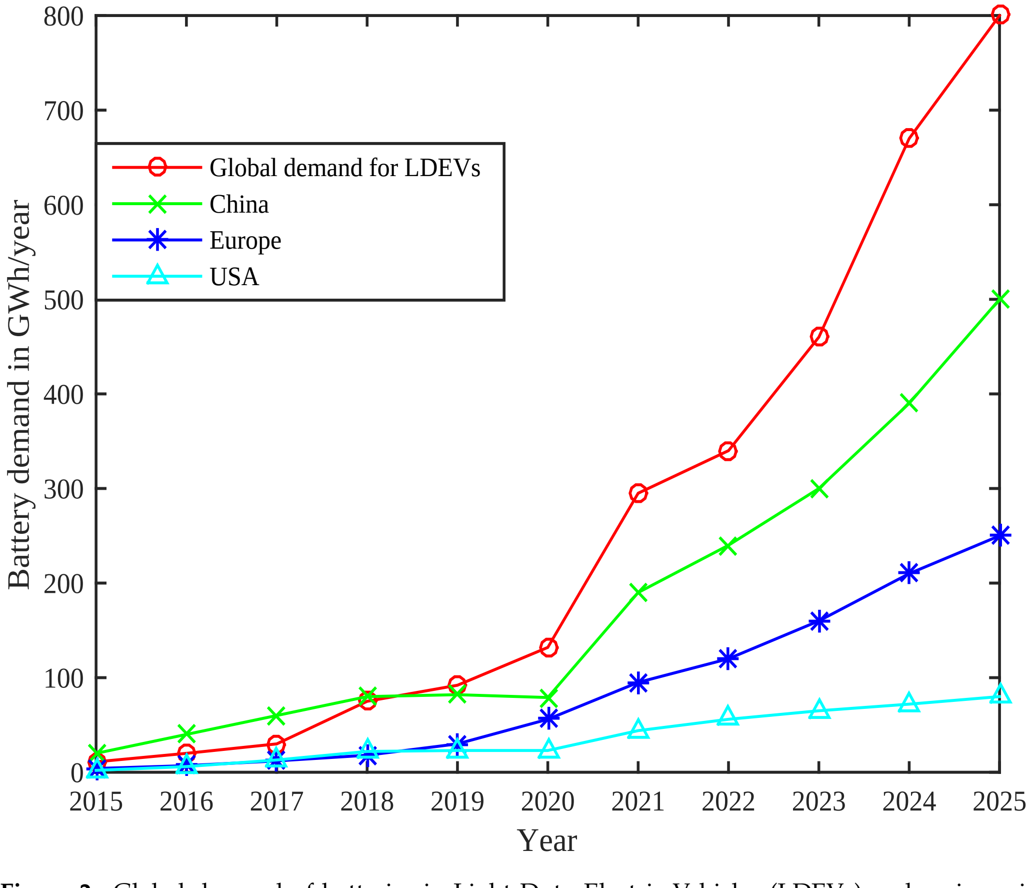

Figure 2. Global demand of batteries in Light Duty Electric Vehicles (LDEVs) and region-wise battery demands.

It is indeed challenging to cover every facet of battery supply dynamic. However, the currently available literature raises several important issues, including forecasting material demands, trade problems, regulatory frameworks, and logistics. Rajaeifar et al. comprehensively discussed resources and energy flows among various supply and value chains of EV batteries [23]. Olivetti et al. critically emphasized the cathode chemistry and cathode materials while concentrating solely on supply components in LBs [24]. Lai et al. provided a review that was limited to the life cycle evaluation of LBs' fundamental framework, categories, benchmarks, methodologies, and technological difficulties [25]. A thorough study on the state of recycled Li-ion batteries was presented by Shahjalal et al., and the new developments in LB second-life applications [26] were also analyzed in detail. Miao et al. in [27] presented an overview of the state of the power of LBs worldwide, focusing on various approaches to handling the spent power of LBs and the types of materials they are linked to. Eftekhari focused on lithium supplies as an economical element for sustainability practices considering the supply situation and strategic plan of LBs for automobiles [28]. In [29], a detailed analysis of commercial and industrial aspects of lithium is presented with a compilation of the various geolocation of lithium sources worldwide. The pertinent LB recycling technology, methods, environmental impact, and products were compiled by Huang et al. [30]. Heidari et al. addressed the anode and cathode materials, the power storage mechanism, and the strategies and difficulties encountered by LB researchers [31]. Despite the large number of LB studies conducted, there is a gap in the research based on the supply chain of various critical LB constituent materials. To bridge this gap, authors have attempted to present a survey of the critical materials required exclusively for EVs. This article presents the various cathode chemistries involved in designing LBs targeted for EVs. Here, we have comprehensively discussed the details of the battery supply chain, which consists of several processing stages to achieve the end product and also discuss the necessary recycling and reuse of the batteries. In addition, the battery-grade commodity price appreciation that is due to various social, political, and geographical circumstances and leading industry policy outlooks is presented. The major contributions of the survey are the following:

- An overview of LB demand for EV application and global contributors.
- Critical EV battery materials and the supply chain dynamics.
- Global leaders and their future policy outlook.

The organization of the survey is illustrated in Figure 3.

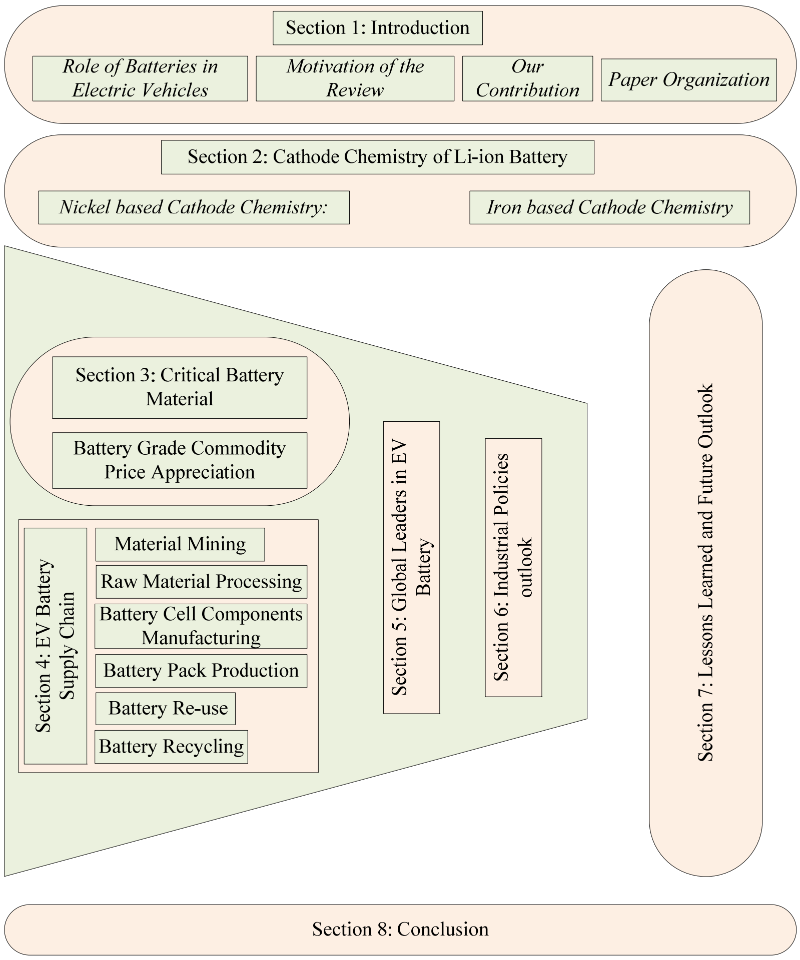

Figure 3. Organization of the paper.

2. Cathode Chemistry of Li-Ion Battery

A crucial distinguishing factor of a battery is the cathode chemistry, which governs its performance, so the availability of cathode material becomes decisive in adopting a battery in the long run. Nowadays, three types of cathode chemistries are primarily favored in the automotive industry: lithium nickel manganese cobalt oxide (NMC); lithium nickel cobalt aluminum oxide (NCA); and lithium iron phosphate (LFP), as illustrated in Figure 4 [32], in which their respective performance parameters are demonstrated in the form of a spider diagram.

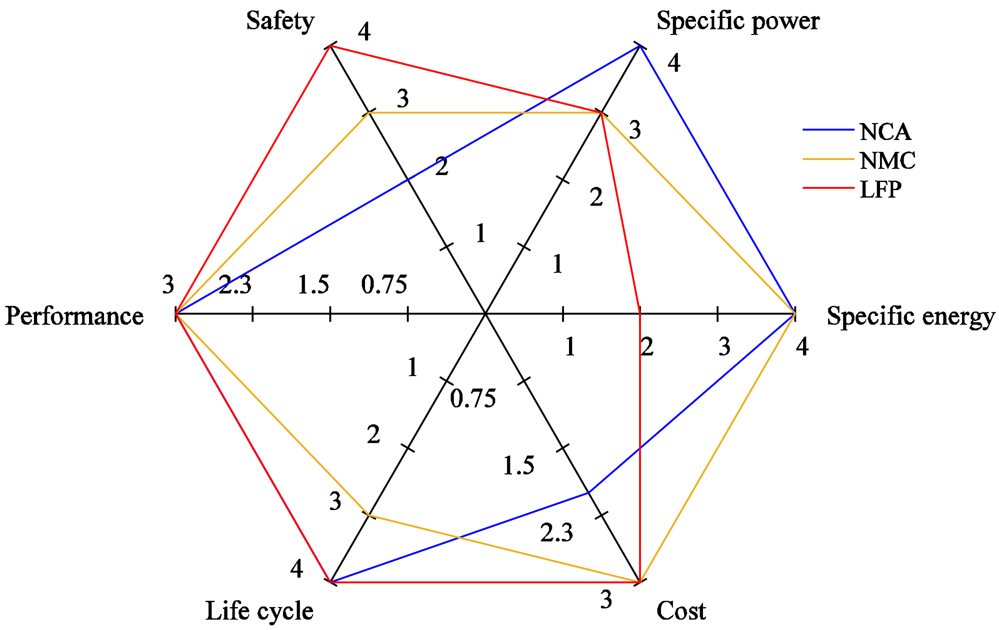

Figure 4. Performance parameters of various battery chemistries.

2.1. Nickel-Based Cathode Chemistry

LB manufacturers used cobalt significantly in their older generation of batteries [33]. However, the emergence of nickel decreased the utilization of cobalt in LBs as nickel-based batteries achieved higher energy densities at a lower cost [34]. With the ever-increasing battery demand, the requirement for battery cathode and anode materials also elevated in 2021. The cathode demand more than doubled compared to the demand of 2020. The battery cell requires a high amount of cathode materials to compensate for the higher energy density of a graphite anode [35]. Therefore, the cathode chemistry is crucial to determining battery performance and material requirements. Due to the high nickel content in NMC and NCA cathodes, they have a high energy density and thus dominate in the EV market [36]. However, the foreseen difficulty in integrating nickel as a cathode material is labor-intensive and complex. NCA batteries are seldom used in present day applications. However, they are still common in long range Tesla variants and electric SUVs. Nickel-based chemistries were vital in the EV market during 2021, with a more than 75% market share of cathode materials due to their superior driving range. The NMC and NCA batteries' market is forecasted to grow significantly between 2022 and 2028.

2.2. Iron-Based Cathode Chemistry

LFP is a cobalt-free battery chemistry that is relatively inexpensive, less likely to catch fire, and has a long-life cycle [37]. LFP typically has a less than 35% energy density compared to NMC batteries, so a significant research focus is devoted to increasing its energy density. As a result, when using LFP, EV manufacturers must make an unavoidable trade-off between energy density and safety. Recently evolved technological improvements of LFP lead to its resurgence, occupying nearly 25% of the total market share, primarily in

China. The notable feature of LFP is its long lifecycle, which makes it an excellent candidate for heavy duty use with repeated charging. LFP chemistry is commonly used in medium and heavy-duty EV batteries [38]. The Chinese government promotes LFP chemistry due to its cost advantage and rigorous use in LDVs. In addition to that, the newly emerging Cell-to-Pack (CTP) technology improves the volumetric energy density, thereby decreasing the dead weight of LPF batteries [39]. The pioneering work on CTP technology and its efficacy were demonstrated by BYD on blade batteries, after which its superior variations were released. The third generation of CTP significantly increases the volumetric energy density of LFP batteries, which will seemingly compete with NMC batteries in the near future. Apart from the Chinese counterpart, major global EV manufacturers including Tesla and Volkswagen are launching high volume EV models based on LFP chemistries. During 2022, almost 50% of the EVs manufactured by Tesla used LFP batteries. EV manufacturers in Europe and the US have gradually planned to incorporate LFP batteries to meet the ever-increasing demand for safe and less expensive EV batteries. The profound limitation of LFP batteries, however, is recycling, as recycling produces iron and phosphorous, which are relatively inexpensive compared to precious metals such as the nickel and cobalt produced during the recycling of NMC batteries. Moreover, toxic off-gassing and recycling costs further add to the woes of the LFP.

3. Critical Battery Material

During the manufacturing of an EV battery, several metals need to be mined to develop a complete battery cell. There are three primary metals needed to develop LBs, which comprise lithium, cobalt, and nickel. These materials are abundantly available on the surface of the earth. However, the supply of these metals greatly relies on mining capacity and the geographical deposition. Mining activities are yet to accelerate to meet the exponential rise of battery demands. The lithium demand doubled from 2017 to 2021. According to the current statistics, 80 kt of lithium was used in 2021. Other than its use in batteries, lithium is commonly used in manufacturing ceramics, glass, lubricants, etc. [4]. With the use of lithium in EV batteries, the demand for lithium has elevated in the current decade. Further, in terms of production and performance, LBs remain uncontested. However, alternative lithium-free chemistries such as Na-ion-based batteries are gaining progress in recent years; though, they are yet to reach the full potential of LBs [40].

Along with lithium, the demand for cobalt has also increased over the years. Cobalt is one of the raw materials required to fabricate super-alloys, hard metals, and catalysts. Cobalt was used in old generation LBs. However, the development of nickel decreased the use of cobalt in the modern generation of LBs. Nickel is a dominant metal in stainless steel production. Battery production, however, requires highly pure-grade nickel known as class-1. The class-1 category has a purity greater than 99.8%, and less than that will come in the class-2 category [41]. Nevertheless, class-2 nickels cannot be used without multistage processing. Since the demand for nickel cathodes is dominant in EV batteries, this is likely to continue until a new technology has evolved which can also participate as a high energy density battery. The Russia–Ukraine conflict has drastically affected the nickel supply chain globally, as Russia is the topmost supplier of class-1 battery-grade nickel. The demands for lithium, cobalt, and nickel are illustrated in Figure 5. The battery cell requires a high amount of cathode materials to compensate for the high energy density of graphite anodes [35]. Therefore, the cathode chemistry is crucial to determining battery performance and material requirements. Nickel and iron-based battery chemistries are explained in detail in the preceding chapter which explains both the advantages and shortcomings of those chemistries. Akin to cathodes, the demand for anode materials also increased alongside the battery demand in 2021. The critical material for producing battery anodes is graphite [42]. Graphite is found naturally and produced synthetically. China has an 80% global graphite supply, being dominant in the world. Countries like Tanzania, Mozambique, Canada, and Madagascar have some graphite stocks. The global demand for cathode and anode materials is shown in Figure 6.

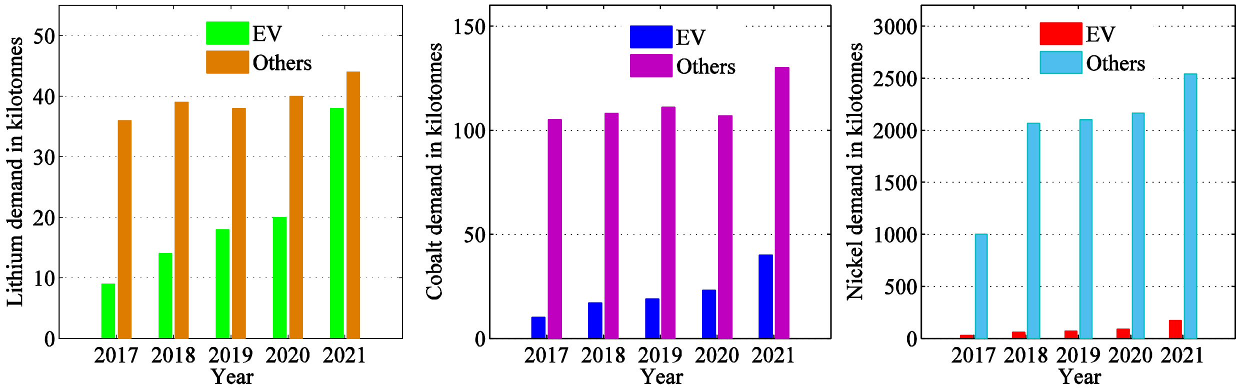

Figure 5. Lithium, cobalt, and nickel demands in EVs and other applications from 2017 to 2021.

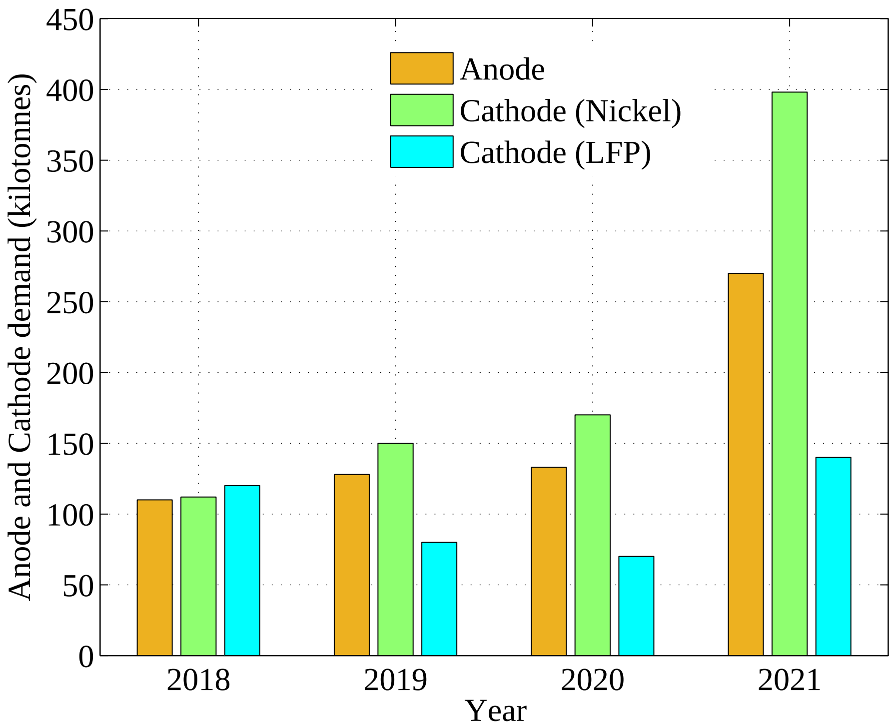

Figure 6. Battery cathode and anode material demand, spanning from 2018 to 2021.

4. Battery-Grade Commodity Price Appreciation

The high demand for batteries impelled the requirement for crucial battery-grade metals. Lithium prices increased dramatically from the first quarter of 2021 to the second quarter of 2022; likewise, cobalt and nickel prices doubled. This price hike is justified by excessive demand and escalating pressure on supply chains because of shrinking supplies [43]. Production challenges due to the COVID-19 pandemic and the war between Russia–Ukraine disrupted the supply chain of core material production. The commodity price surge depends on the production and supply of the new mines and the expansion of existing ones. However, the high price of a commodity may offer some long-term benefits, such as increasing supply investments to expand the industry capacity [44]. Figure 7 shows the battery and critical battery metal price appreciation over last five years. It shows that there is an unprecedented demand of lithium followed by nickel and cobalt. Therefore, it will be difficult to further depreciate battery prices as it has been seen in 2021.

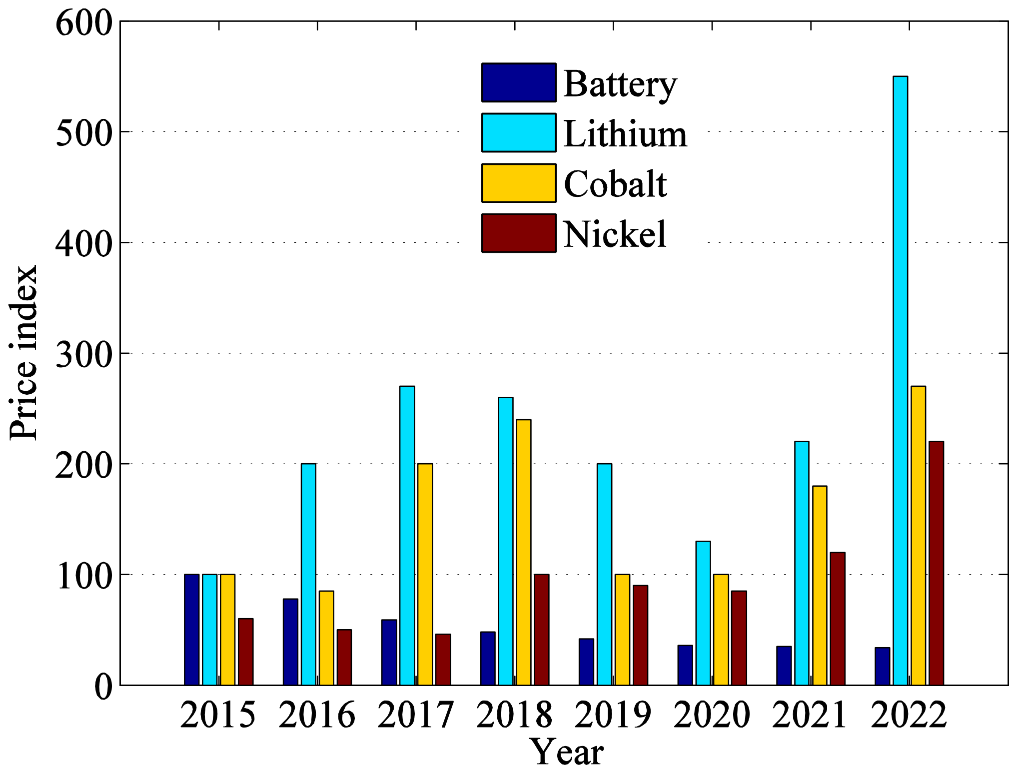

Figure 7. Battery metal price appreciation and battery price depreciation over the last eight years [4,43].

5. EV Battery Supply Chain

The manufacturing process of EV batteries comprises several stages, where communication with each stage is through a supply chain. The supply chain consists of the steps starting from extracting the necessary mineral ores, refining, materials' synthesis, battery cell production, and recycling [45]. In order to comprehend the futuristic possibilities of EV batteries, it is crucial to have knowledge of the various intermediate phases in the supply chain dynamics. Figure 8 depicts the schematic representation of the process flow of EV battery manufacturing. Figure 9 illustrates the geographically concentrated material required for the EV supply chain.

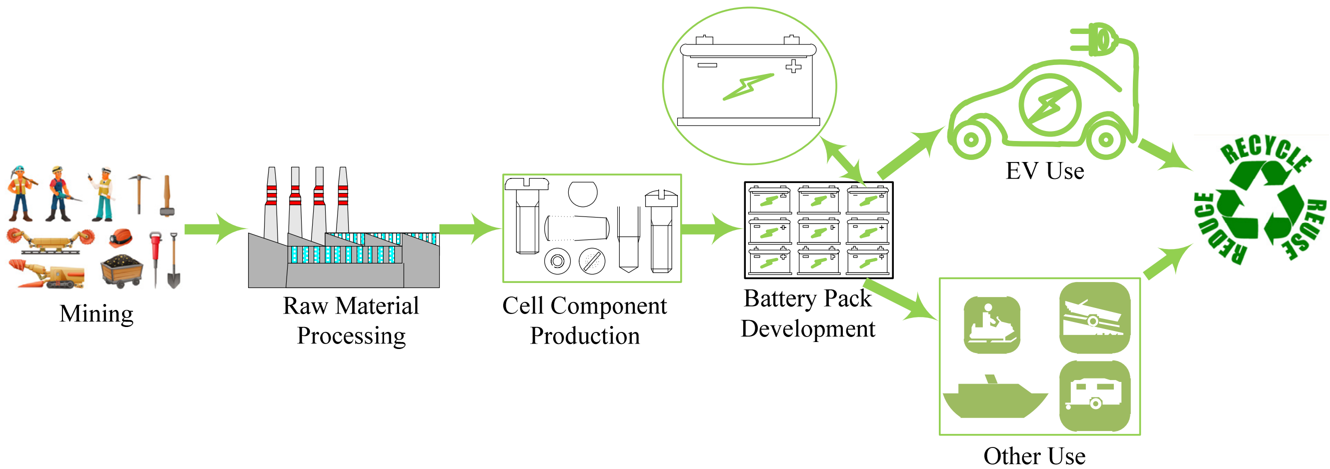

Figure 8. EV battery supply chain schematic.

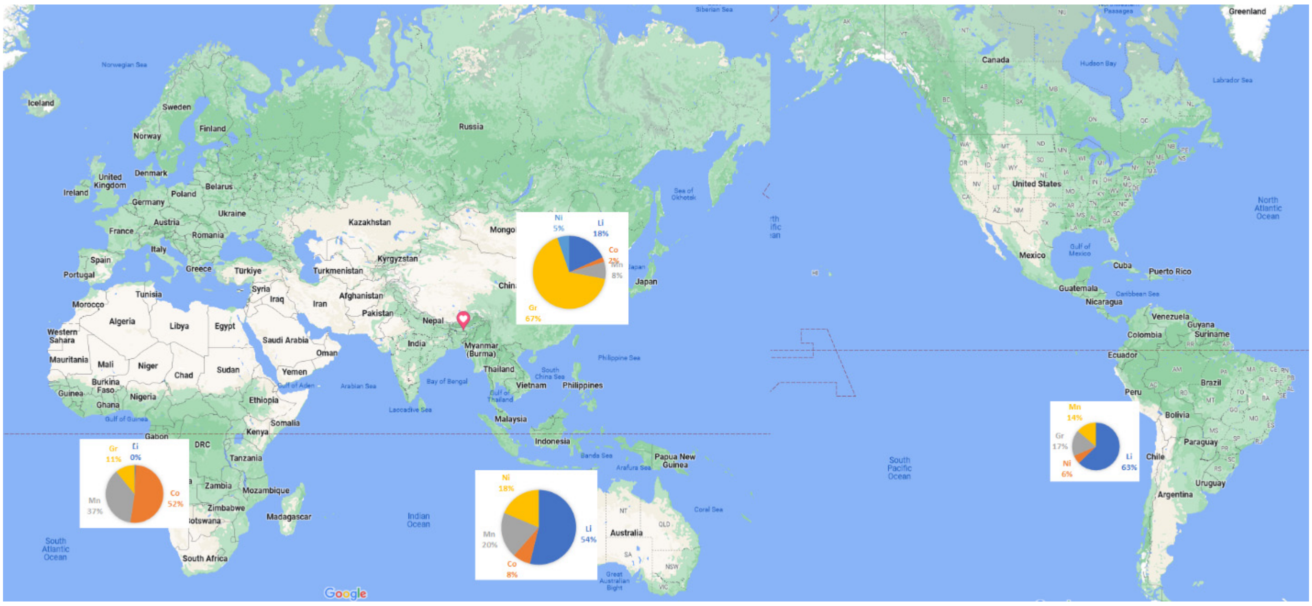

Figure 9. Geographical concentration of critical battery materials [4].

5.1. Material Mining

Lithium, nickel, cobalt, graphite, and manganese are the five indispensable materials required to manufacture LBs. Lithium is produced mainly from brine and hard-rock deposits (spodumene); both are used to extract specific products with differing values [46,47]. The countries rich in lithium brines are Bolivia, Argentina, and Chile. Brine deposits often contain hefty quantities of sodium, potassium, magnesium, and boron. These elements offset the costs of brine pumping and processing. The manufacturing process is divided into three distinct steps: (i) solar evaporation in shallow ponds, which takes several months to complete in order to collect lithium in the range of 1–6%; (ii) the removal of byproducts such as boron and manganese by dint of chemical processing; and (iii) the extraction of lithium carbonate. Lithium carbonate is popularly used as a primary material to design battery cathodes, targeted cathodes having a low percentage of nickel content. Lithium hydroxide is an additional essential lithium product produced by incorporating an extra process that involves heating a mixture of lithium carbonate and salt lime. Australia has the major mine fields for lithium hard rock, which is composed of lithium and aluminum. In the recent past, brine was the primary source of lithium; however, the demand surge of lithium has driven spodumene mines to accelerate recently. Lithium extraction requires a specialized mining process for mining industries. The lithium supply chain is shown in Figure 10.

Two distinct nickel deposits are found in nature, namely: sulfide and laterite [48]. Russia, Canada, and Australia have huge sulfide deposits from which high-grade nickel can be extracted. The class-1 battery grade nickel can be quickly processed. Laterite, however, contains low-grade nickel that requires energy-intensive process steps to realize battery-grade nickel. Indonesia, the Philippines, and New Caledonia are the primary laterite sources. Unlike lithium, nickel production is relatively less concentrated. Hence, a few companies supply half of the global nickel production. Over the last five years, nickel production on a global scale has climbed by 20%, primarily due to nickel-favoring project initiatives in the Asia Pacific. Indonesia and the Philippines have implemented nickel policies, accounting for more than 45% of the global nickel production. Figure 11 illustrates the supply chain associated with the global nickel production.

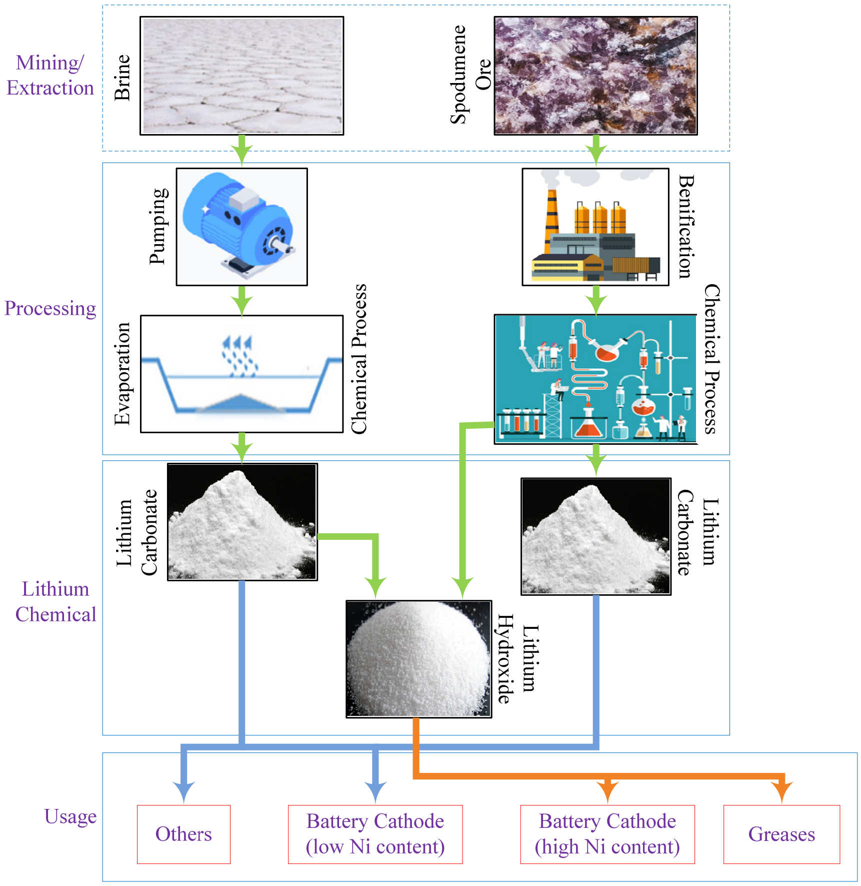

Figure 10. Lithium supply chain.

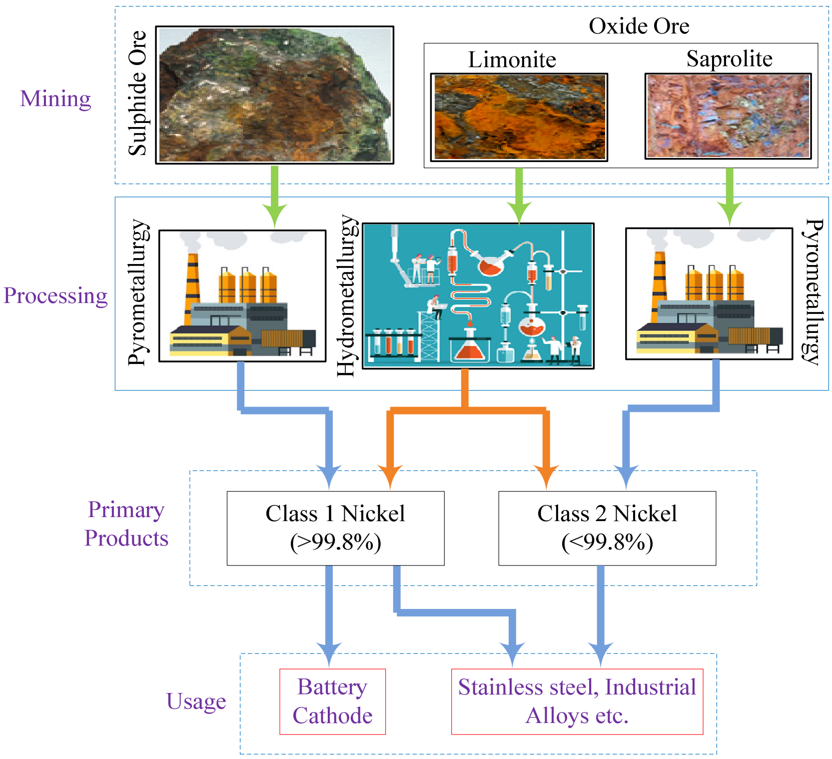

Figure 11. Nickel supply chain.

Cobalt was previously employed in constructing super-alloys, catalysts in petrochemical industries, magnets, and magnetic recording media. However, with the increasing production of EVs and nations adopting policies for sustainable mobility by transforming the automotive industry from ICEVs to EVs, a sudden surge in cobalt demand has resulted in an escalation of cobalt prices in the market. During nickel and copper mining, 60.7% and 29.3% of the cobalt used worldwide is found as a by-product [49]. The Democratic Republic of Congo and Switzerland are the primary cobalt producers, with over 70% of the world's cobalt production being sourced from these two countries. China is the leading exporter of cobalt, processing more than 70% of the global cobalt supply, mainly imported from the Democratic Republic of Congo. Finland, Belgium, and Canada are also some of the notable cobalt producers. The supply chain involved in cobalt is illustrated in Figure 12.

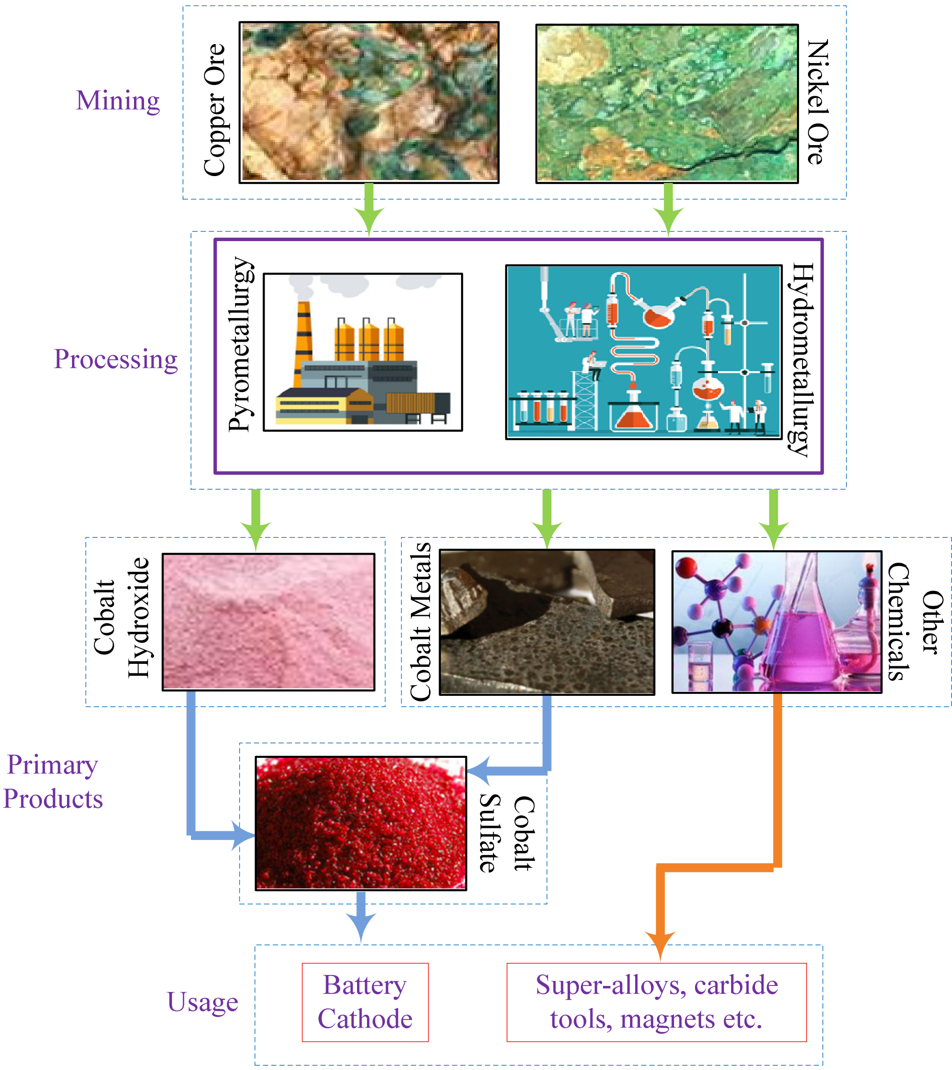

Figure 12. Supply chain of cobalt.

Graphite is the dominant battery anode material; China dominates the market with 80% global supply. Some other countries, including Tanzania, Mozambique, Canada, and Madagascar, also share graphite production shares. Manganese is widely disseminated across the world compared to other battery-grade metals and is believed to meet the global supply demand. Therefore, it can be extracted at a relatively low cost. The dominant manganese ore manufacturers are South Africa, Australia, Gabon, and China.

5.2. Raw Material Processing

In order to achieve highly purified battery materials, various energy intensive processing steps are indispensable. The refining process involves an intense industrial process with heat and chemical treatment to transform raw ore into chemicals such as lithium carbonate, lithium hydroxide, or cobalt and nickel sulphate [50]. Battery-grade material processing further involves an additional process complexity. Lithium carbonate has a wide use in various lithium demands; however, it is not suitable for LBs. Lithium hydroxide is indeed more desirable for high-nickel chemistries, and it can be effortlessly extracted from hard rocks. The nickel process technology involves the method of high-pressure acid leaching (HPAL), which can produce class-1 nickel from lower-grade laterite resources [51]. Another nickel source named nickel matte can be produced from laterite resources. However, it suffers from a high level of pollution as compared to the conventional process. The raw material processing industries are highly concentrated in some geographical regions. Five companies contribute 75% of the global production of any EV battery material. Mining companies more often undertake their refining, but they may occasionally outsource it to a third party. Manganese, on the other hand, is widely spread across various geographies. China is the leading manganese supplier, accounting for about 90% of the global production capacity. Australia, Europe, Indonesia, and the USA have recently started plants to extract battery-grade manganese.

5.3. Battery Cell Components Manufacturing

A battery comprises individual components such as a cathode, an anode, electrolytes, and separators [52]. To produce these elements, sophisticated chemical processing of several materials and process engineering is required. Active battery materials need the most complex processing steps; for example, lithium hydroxide and nickel sulphate undergo multiple processes using specialized syntheses for manufacturing active cathode materials. More than 55% of cathode materials manufactured worldwide are owned by seven firms, among which Sumitomo (Tokyo, Japan), Tianjin B&M Science and Technology (Tianjin, China), Shenzhen Dynanonic (Shenzhen, China), and Ningbo Shanshan (Ningbo, China) are the major players. Unlike cathodes, graphite anode material processing is more mature and recognized. Adding small and increasing silicon fractions into the graphite anode improves the anode performance [53]. Graphite is the leading material used in anodes and can be procured naturally or developed synthetically in a laboratory. It is pertinent to mention herein that graphite involves sophisticated processing; however, it is still the preferred anode material. Natural graphite found as flakes are transformed into spherical forms to maintain homogeneity in the anode, whereas refinement of hydrocarbons is done to make synthetic graphite. Synthesis of anode materials is even more intensely focused, with four companies holding 50% of the global production. Six companies, all based in China, contribute more than 65% of the anode materials made globally. Separators are microporous membranes engineered from polyethylene or polypropylene [54]. They are often coated with ceramic to improve the safety of EVs. Separator production is also a centralized business, accounting for half of the world's capacity. Electrolytes consist of salts and solvents, both requiring synthesis and mixing. The existing cellular component manufacturing industry is highly specialized and oriented toward producing specific components.

5.4. Battery Pack Production

There are two major stages of producing battery cells: electrode manufacturing and cell fabrication. Out of those, the cell fabrication technology is well established [55]. The process requires a highly controlled clean room to avoid unwanted impurities, thus becoming more energy intensive. Another critical aspect of these processes is to take care of pollution. Typically, low-carbon sources of electricity are used to drop emission levels during cell production. Manufactured cells are housed in a module frame, which is then integrated into a battery pack. Finally, the batteries, control system, electronic circuit system, and sensors system are encapsulated in the housing structure. The battery production industry is highly concentrated since cell production and development require a considerable capital investment. China, Korea, and Japan were the top three battery cell producers in 2021. Recently, Europe and North America have been involved in the cell manufacturing process, although mostly they are in conceptual stages.

Most cell producers in Japan and Korea are well-established corporations with years of expertise in producing batteries for consumer devices. Chinese businesses such as CATL and BYD started making cells for consumer devices in the early nineteen-nineties before making batteries for electric vehicles. Although policies for manufacturing batteries have been enacted in Europe and North America, most are currently in the planning stages. In order to meet their demands for batteries, EV manufacturing firms such as Tesla and CATL have most recently been actively engaged in mining and producing raw materials.

5.5. Battery Re-Use

In order to reuse or recycle a battery, manufacturers will need to refurbish the battery for other uses in a second life. Mainly, a battery's second life applications involve stationary storage [56]. Typically, a used EV battery has more than 80% of its usable capacity for reuse in secondary applications [57]. It offers an added value to the battery's materials. During refurbishing, a battery needs to disassemble from the battery pack, the module needs to be reassessed, and it needs to be repackaged for new applications. The principal cost entailed in the reuse process is the logistics involved in collecting, testing, disassembling, and repacking. Despite having an additional value, reuse faces issues from reliability, economy, regulatory, and competitive advantages [58]. Conventional retired power (RP) LBs constitute iron or aluminum; an admixture of graphite, conductor, binder, and electrolyte is layered on copper foils to serve as the retired LBs' anode substance [59]. Aluminum foils embedded with cathode materials, conductors, polyvinylidene fluoride binders, and fluoride salts are typically used as the cathodes in RP LBs. Short contacts between the opposite electrodes are also averted using the cathode–anode separator element [60]. The recycling of retired LBs has a multitude of advantages which can be categorized into three perspectives: sustainability—it will significantly decrease resource utilization; economical—it minimizes the expense of raw material procurement; political—it lessens reliance on imports, which has protracted geopolitical implications [61]. The echelon utilization of retired LBs has recently become a focus of study. The problem of echelon utilization of large-scale RP LBs can be resolved, which has enormous benefits for the economy and the environment. The worldwide RP is predicted to surpass 600 kt by the end of 2025 [62]. If retired LBs are deserted, considering their enormous numbers, they will pollute the ecosystem, and a tremendous amount of materials will be wasted. This contravenes the 4R concept: recycle, reuse, reduce, and recover [63,64]. On the other hand, echelon utilization is thought to be one of the best options for treating RP LBs and is anticipated to become more common in the coming years of study [65]. Grid energy storage and 5G base stations are two examples of echelon utilization that can completely utilize the leftover energy in RP LBs [66].

5.6. Battery Recycling

Three main methods are used in lithium-ion recycling: pyrometallurgical, hydrometallurgical, bioleaching, and direct recycling [67–69]. The battery is melted in a hot furnace to recover some of the cathode metal in pyrometallurgy. Pyrometallurgy employs extreme heat to transform metal oxides into cobalt, copper, iron, and nickel alloys. Although it has a straightforward process and a reasonably mature technology, the main drawbacks are its high cost and high environmental pollution. Hydrometallurgy is a metal recovery method involving aqueous solutions to perform leaching processes to precipitate a particular metal. In hydrometallurgy, specialized solution reagents are primarily used to leach the targeted metals out from the cathode substance [70]. Although it is a highly effective and power-efficient method, its drawbacks include a lengthy production time and a complicated process. Combinations of both pyrometallurgy and hydrometallurgy are also used due to their advantages in sorting starting materials for cells. The bioleaching technique uses bacteria to retrieve precious metals, but it is challenging because the bacteria need a substantial amount of time to grow and are easily susceptible to contamination.

Direct recycling is dismantling the anode and cathode components from RP LBs, followed by the maintenance, processing, and production of the components for reuse. Direct recycling has a smooth process, is inexpensive, and causes little environmental damage; however, it needs more technical maturity and is challenging to commercialize. However, pyrometallurgy and hydrometallurgy are the recycling techniques that are most frequently used in industries. The German company Accurec created a pyrometallurgy technique primarily used to recover Li-metal and Co-alloy. Co(OH), Li_2CO_3, and Li_3PO_4 are primarily recovered using the hydrometallurgy technique created by the French firm Recupyl. The Umicore company in the United States created a pyro- and hydrometallurgy process that is predominantly used to recycle $CoCl_2$ and $Ni(OH)_2$. China is leading battery recycling, accounting for about half the global capacity of 200 kt/year. Although most of the recycling industries are independent, other supply chain industries such as mining, manufacturing, and process industries are also starting to enter this market. Unlike the other recycling methods, direct recycling is an emerging process that offers advantages to improving recycling efficiency. It also increases the energetic and economic value of cathodic processing and eliminates the need for their synthesis of raw materials. For example, SK Innovation and Kia have developed recycling initiatives to reuse batteries for stationary storage. Recently Renault, Veolia, Solvay, BMW, Umicore, and North volt have also initiated the closed-loop process methodology for reuse and recycling. The US National Renewable Energy Laboratory has implemented RP LBs for echelon utilization or power storage in both business and residential structures [71]. ABB has collaborated with General Motors to produce peak shaving and valley-filling equipment paired with renewable energy power generation and backup power supplies for small-scale residential and business use, using the retired LBs from Chevrolet cars. Toyota has stored and supplied electricity for the facility using the retired batteries from its Camry. Additionally, a robust control system has been developed to nearly double the serviceability of retired batteries [72–74]. Retired batteries are used in China as part of a pilot scheme for the Beijing Daxing electric taxi charging station that the China Electric Power Research Institute, State Grid Beijing Company, Beijing Jiaotong University, and other research institutions collectively founded. This initiative regulates the output power of transformers and preserves a constant voltage level. A Chinese company started a project in the communications sector to disassemble and recycle old electric vehicles, using the retired batteries as a backup power source for things such as base stations and street lamps to promote energy efficacy and stability. The use of echelon utilization is expanding globally as industries and academic institutions are actively researching to develop cutting-edge technologies for commercialization [75].

Although there are numerous prospects, there are still several technological constraints with the reuse, recycling, and echelon utilization of LBs [76,77]. The recycling and reconfiguration procedures need to be more flexible to handle the intricate echelon utilization of RP LBs. Furthermore, safety concerns, assessment techniques, economic viability, supply chain development, and regulation and authorization are the primary obstacles to the reuse of LBs. Another significant issue is the safety management of the entire life cycle of exhausted LBs [78]. Reutilization could result in thermal runaway or multiple disastrous events if the reliability of the process cannot be assured. Another significant issue with RP LBs is the performance assessment, which assesses the utility of the LB in advance of screening and regrouping. There are many irregularities and difficulties with the performance assessment process. Constructing an entire supply-demand pipeline for RP LBs is yet another technical obstacle. Creating a supply-demand network for the echelon usage of RP LBs depends on the business, the government, or independent organizations. The supply–demand chain, which favors all the parties, is still in its infancy because the supply chain requires the completion of numerous units. Recently, a few efficient battery reuse methods have also been put forth. However, some technologies have yet to receive widespread promotion and adoption due to a dearth of professional standards and certification. Even if an efficient echelon usage technology is created, it can be challenging to be endorsed and accepted by customers without the necessary certifications and regulations. In the near future, LBs will continue to be the preferred option for EVs.

The scale of RP LBs has grown significantly lately due to the rising number of EVs, and the issue of echelon usage is becoming a study focus. Numerous organizations and governments are also introducing pertinent policies to strengthen the industrial supply chain. The present state of world development is focused on green economies and sustainability, and echelon usage strategies and models also place an emphasis on these problems.

6. Global Leaders in EV Battery

While some countries are making headway in the battery value chain, China still dominates all EV battery supply chain stages. Figure 13 illustrates the different industries associated in the EV battery supply chain with their respective market share [4]. China accounts for 70% of its positive electrode materials and 85% of the global production capacity of negative electrode materials. They also process raw materials for lithium, cobalt, and graphite in China, which has half the world's production capacity. Europe has produced a significant number of EVs in recent years but has been unable to keep up with the rest of the supply chain. The US still contributes little to the global EV battery supply chain. South Korea and Japan have significant stakes in the downstream raw material processing supply chain, especially in manufacturing cathode and anode materials. However, some caveats should be considered by the industries, such as the availability of technical resources, quality assurance and abundance of the critical battery materials, capital, and above-ground limitations. The attributes mentioned above are crucial since they can hinder the development process and undermine the reliability of EV batteries in the future.

Due to the high geographic concentration of the raw materials for batteries, there are severe limitations on supply and extraction. For instance, half of the global lithium stock is supplied from Australia, while 70% of cobalt extracted worldwide is contributed by the Democratic Republic of Congo. Nickel supply is further diverse despite Indonesia having a 40% global concentration. Russia is one of the leading sources of nickel class-1 that is suitable for batteries, generating almost 20% of its production worldwide. Therefore, considering the scattered nature of battery materials in various geographic regions, the supply chain of materials is likely to remain the same. With almost a quarter of the world's deposits, mainly in Turkey and Europe, controlling the most considerable portion of the market, there is a real potential to diversify the mining for natural graphite. Holding 22% and 17% of the world's deposits, Brazil has enormous opportunities for mining and extracting nickel and graphite. However, there are certain restrictions that need to be taken into account when considering deposits, such as material quality (which is crucial to battery metals), financing, and above-ground limitations that may reduce their capacity to serve as a dependable source of future supply.

Contrarily, it is anticipated that the downstream supply chain concentration will change soon as more nations see the potential of EVs. By 2030, 25% of the world's capacity for battery manufacturing will be located in the US and Europe if existing policies, pronouncements, and investments come to fruition. Parallelly, new alliances are forming among motor companies in Europe and the US with governments regarding the manufacture of cathode materials. For instance, Volkswagen revealed a new collaboration with Umicore to upscale the productivity of cathode materials in Europe. By 2030, Redwood Materials and L&F propose constructing a US manufacturing plant to produce cathode materials for 5 million EVs annually; a similar facility is also targeted in Europe. The European cell producer Northvolt plans to produce its own cathode material at a rate of more than 100 GWh annually.

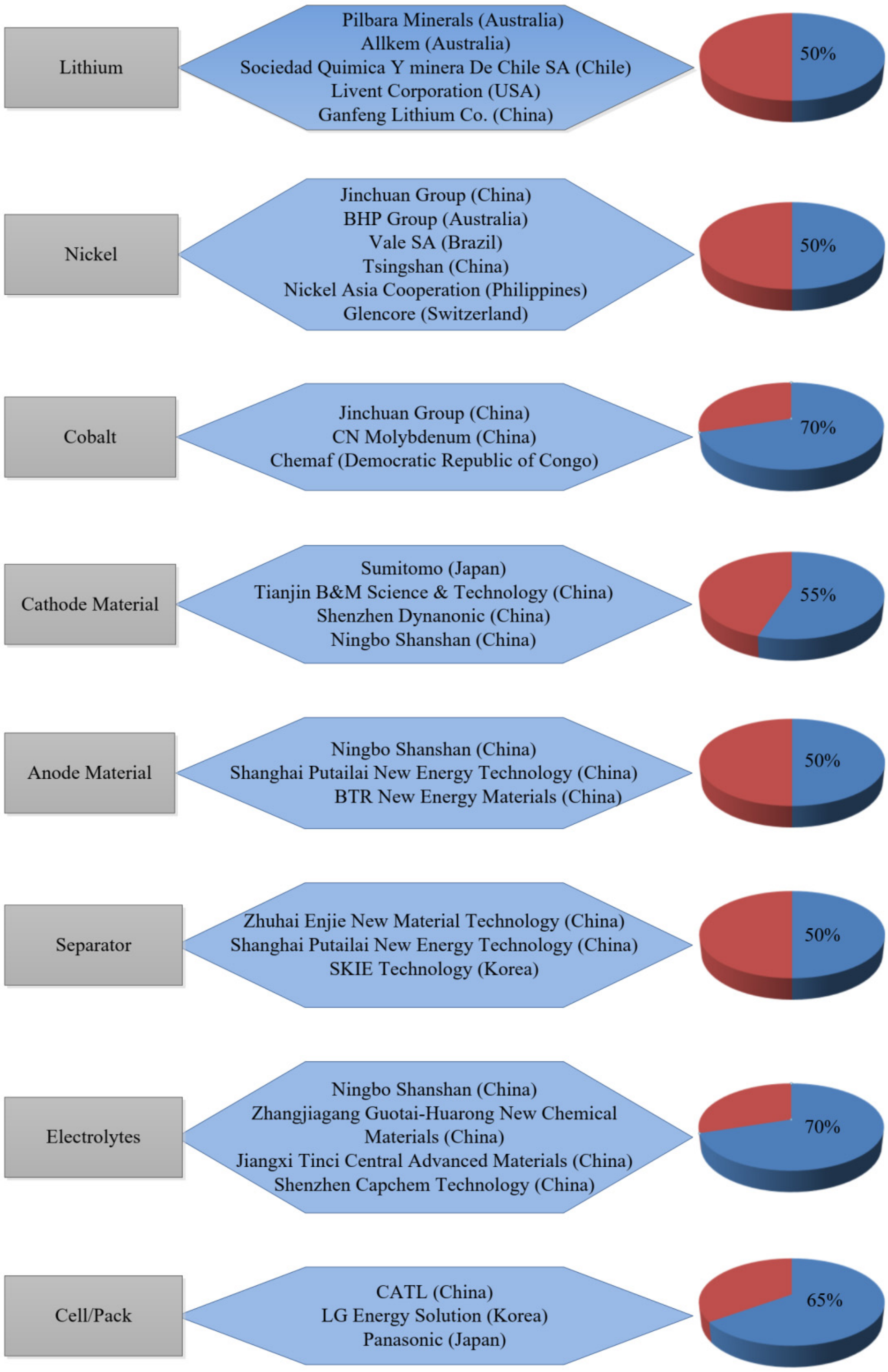

Figure 13. Industries associated in the various steps of the EV battery supply chain with their respective market share.

7. Industrial Policies Outlook

In order to establish and grow their relevance within integrated battery supply chains, nations all over the world have adopted industrial policies. Leading EV manufacturing nations seek to move up the supply chain from producing EV components and vehicles to securing secure upstream supply and metal and mineral refining capabilities to curb the material shortage. Due to its forward-thinking policies supporting industries over the past ten years, China holds a 77 percent market share in the global EV industry. Along with Japan, which has 4% of the worldwide production capacity, Korea, which has 5%, has lately unveiled sizable financial initiatives to mark its presence in the battery and electric vehicle industries. Although the European Union has made significant investments in R&D over recent years, establishing the supply chains required for an EU battery manufacturing industry to evolve will probably take some time. Parallel to this, the US has already redoubled its efforts to develop indigenous supply chains for EVs and batteries, especially by exploiting its vital automotive and mineral resource industries. Some newcomers, such as Indonesia and Thailand, are strategically concentrating on producing batteries, electric vehicles, and the distribution of materials, maintaining close ties with the Asian market by utilizing their geographical advantages. They have attracted several investments from major EV producers due to their geolocation.

The Canadian government approved USD 398 million in the first quarter of 2022 to General Motors of Canada to expand EV facilities by modernizing and retooling them with cutting-edge technologies [79]. China also implemented new regulations supporting EV adoption and production by offering financial incentives to consumers and businesses. In March 2022, there was a collaborative alliance between the European Battery Alliance and the US Li-Bridge to gear up the next generation of LB technology [80]. Europe has also organized the Batt4EU Partnership among the industry and R&D stakeholders to promote the new innovations in LB supply chain technology [81]. India is focusing on advanced automotive technology and battery cells to support the supply chain dynamics [82]. With the recent discovery of a lithium deposit of 5.9 million tons in Jammu and Kashmir, India will try to set its footprint in the global market [83]. Japan's strategic energy plan targeted the domestic LB production by up to 100 GWh in the next seven years [84]. Korea has launched an ambitious project to lead a few sectors of the EV battery supply chain by 2030 [85]. The National Blueprint for Lithium Batteries launched by the USA is to maintain a steady flow and storage of raw materials for domestic use [86]. Thailand promoted to increase the domestic EV production by up to 30% by the end of this decade [87]. Indonesia has also projected 0.6 million LDVs by the next seven years [88]. The United Nations Economic Commission for Europe hosts the International Conference for Harmonization of Automobile Regulations, which creates legally enforceable laws encompassing technical criteria to increase vehicle safety and lessen environmental impacts [89].

To provide an uninterrupted flow of supply chains worldwide, the large-scale mineral and metal suppliers of EVs have begun to concentrate not just on mining but also refining. Mineral-rich nations work hard to enact laws that guarantee a consistent supply of the minerals needed for EV batteries. Table 1 demonstrates the various leading countries and their policies that enable a sustainable battery supply chain for the next generation's electrification.

Table 1. Leading countries and their policies that enable a sustainable battery supply chain.

Country	Leading Minerals	Enabling Policies [90–95]
Australia	Lithium, Nickel	■ Government-approved loan facility of USD 980 million to enhance the supply of critical minerals. ■ New fund allocation of USD 1.5 billion is announced to expand the existing processing capacity. ■ Additional fund of USD 1.8 billion proposed to expand the capacity of nickel and cobalt mining, processing and recycling facilities in New South Wales.
Chile	Lithium	■ Launched a contract auction to explore four lakh tones of lithium.
China	Nickel, Cobalt, Graphite	■ Government introduced a five-year plan that aimed to improve efficient mining technology which focused on environmental safety during operation.
Indonesia	Nickel	■ Launched the export ban on nickel-based product to strengthen the domestic refining capacity.
Japan	Cathode materials	■ Released a strategic plan that aimed to expand the capacity of the domestic EV battery production.

8. Lessons learned and future outlook

Globally, nations have implemented measures to hasten the transition from internal combustion engines to electric vehicles. As a result, there will be a great demand for raw resources. The highly varied battery chemistries will be crucial to meeting the future raw metal needs of the battery industry. To meet the unique EV demands, diversification will increase significantly through 2030. Premium category vehicles are likely to adopt high energy density batteries such as nickel chemistry-based batteries, lithium nickel oxide, or lithium-manganese-rich batteries. Low-range urban vehicles will presumably adopt LFP batteries. Unlike them, mid-range vehicles are expected to use manganese-rich chemistry batteries.

Although lithium-ion batteries have demonstrated their efficacy in EVs, they are not ideal for stationary storage. Moreover, the battery technologies for EVs' are still in their nascent stage, and there is significant headroom for research in this direction. Therefore, there is continuous exploration for a new battery technology that would have attractive features such as cost-effectiveness, high package density, ease of raw material collection, low development challenges, free of fire risk, and improved ageing. Some of the recently developed alternate battery chemistries along with their advantages and limitations compared to Li-ion batteries are illustrated in Table 2.

We can conclude that the future of battery chemistries is uncertain because of the fluctuating market demand for critical resources as well as the emergence of several alternate battery chemistries. As a result, the market for batteries could face tough competition from new battery technologies. Nevertheless, with high competition in both academia and industry, batteries with a low charging time, low cost, and high boosting capacity are in the highest demand.

Researchers in the mining business predict that the demand for the metal used in EV batteries will remain stable through 2025. Beyond that, though, things might still need to be determined. However, supporting the mining endeavor and mineral processing facilities might take a lot of work. In addition, it is necessary to build new cathode and anode manufacturing facilities. Moreover, EV manufacturing facilities are essential for maintaining an equilibrium between supply and demand. The anticipated demand for battery metals might grow considerably higher in the net zero emission scenario by 2025.

Nevertheless, beyond that, the situation could be uncertain. Furthermore, significant effort may be required to bolster the mining project and mineral processing plants. In addition to that, new cathode/anode manufacturing plants need to be deployed. Moreover, EV production plants are indispensable for balancing supply and demand. The projected demand for battery metals in the net zero emission scenario by 2025 could be significantly higher. From 2015 to 2021, the average battery size increased by 10% annually. By 2030, the battery size is expected to have multiplied by up to 30% based on this pattern. Considering the case of net zero, this tendency could be interrupted by implementing regulations prohibiting EVs with incredibly large batteries. The 16% increase in battery metal requirement can be prevented if battery sizes stay constant by 2030.

Additionally, the recently established advancement in mining for minerals can aid in bridging the supply–demand disparity for LB metals. For instance, a new lithium extraction process named Direct Lithium Extraction (DLE) bypasses time-consuming steps such as brine water evaporation and the impurity removal process [96]. Several mining companies are attempting to adopt the DLE with the help of joint ventures with DLE-technology developing industries.

In recent years, industries have offered quick, seamless services with improved quality, efficiency, and dependability owing to adopting new technologies such as cloud computing, the Internet of Things (IoT), data processing, and blockchain. The exponential growth of EV adoption necessitates the evaluation and combination of a large number of battery supply chain factors. The use of technology such as the blockchain platform, which monitors supply chain execution, allows for greater control over battery performance and environmental impact. Additionally, blockchain technology aids in tracking batteries and recognizing the critical issues in associated markets. Greater transparency is made possible throughout the complete supply chain, including production, reusing, recycling, and disposal.

Table 2. Comparative analysis of state-of-the-art battery technologies with Li-ion batteries.

Battery Technology	Chemistry Incorporated	Advantages	Limitations
Solid-state	Use of solid electrolyte	✓ High package density ✓ Longevity ✓ Fireproof	× Low scalability × Degradation over time
Lithium sulfur	Sulfur used as battery cathode	✓ Sustainability ✓ Efficient, four times more energy density ✓ Availability ✓ Less energy required during production	× High Corrosion × Low life
** Cobalt free lithium-ion	Cobalt is not used to stabilize the cathode	✓ Less expensive due to absence of cobalt.	× Low efficiency
Sodium-ion	Saltwater is used as electrolyte	✓ Affordable ✓ Low fire risk ✓ Performs better at low temperature ✓ Recyclable	× Low energy density × At present, inefficient for use in EVs
Ion-air	Reversible rusting is used to produce energy	✓ Highly affordable ✓ Availability ✓ Cheaper ✓ Lasts longer	× Large size × Slow recharge
Zinc-based	Zinc ion is used	✓ High storage capacity ✓ Affordable ✓ Non-toxic ✓ Availability	× Suffers from several technical challenges (like short circuit).
Silicon anode lithium-ion	Anode made of silicon	✓ Enhanced energy density ✓ Cheaper	× Impractical driving range × Increase in Mass
Lithium Tungsten	Nanotechnology based	✓ Fast charging ✓ Efficient power usage	× Production cost
Organosilicon Electrolyte	Co-solvent in lithium-ion electrolyte to extend longevity	✓ Environment friendly ✓ Longevity ✓ Environment friendly ✓ Non-flammable and non-toxic	× High initial cost × Most disadvantages of lithium-ion batteries are ingrained
Metal Hydrogen	Using pressurized hydrogen	✓ Longevity ✓ Maintenance free ✓ Light weight	× High Cost × High rate of self-discharge

** LFP (lithium-ion phosphate) is cobalt free battery; however, it has an inadequate energy density for its use in EVs.

9. Conclusions

In this work, we have presented summarized information on the EV battery raw materials, supply chain dynamics, major supply industries, and the global trend of battery resources. The existing literature does not have sufficient discussions on various aspects of LB supply chain dynamics and related industry outlooks. Therefore, to bridge this gap, we have focused on a comprehensive review on the aforesaid issues and their associated challenges and future prospects. The main conclusions of this work are summarized as follows:

(1) The commodity price appreciation significantly influences the LB manufacturing industry expense; however, it has a long-term benefit to improving the capacity expansion and supply investments. The LB supply chain is a collective attempt of several industry chains such as mining, processing, recycling, etc.
(2) China is still the global leader in almost all supply chain steps. Despite the massive growth of EV fleets in Europe and the USA in recent years, they still lack battery production. Nevertheless, new investments are being directed to the other regions of the world and are expected to increase the production capacity by 2030.
(3) The diversification of EV demands is crucial for future EV fleets because of varied battery chemistries. For example, premium category vehicles are likely to adopt NCA/NMC batteries; low-range urban vehicles will presumably adopt LFP batteries.
(4) Nations all over the world have adopted industrial policies to develop a sustainable battery supply chain. Leading EV manufacturing nations seek to move up the supply chain from producing EV components and vehicles to securing secure upstream supply and metal and mineral refining capabilities to curb the material shortage. They have adopted several policies to promote and incentivize the battery material mining and processing industries.
(5) In order to meet the demand of the global net zero scenarios, innovations in the battery supply chain could bring forward advanced extraction and processing technologies in the near future. Cloud, IOT, AI, and blockchain technologies all assist in tracking output while recognizing the key issues in related markets. Greater transparency is made possible throughout the complete supply chain, including production, reusing, recycling, and disposal.

Author Contributions: Conceptualization, P.B.; writing—review and editing, P.B., L.D. and B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the European Commission's H2020 TWINNING Networking for Excellence in Electric Mobility Operations (NEEMO) Project, under Grant 857484.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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