resources

Review

Review of Lithium as a Strategic Resource for Electric Vehicle Battery Production: Availability, Extraction, and Future Prospects

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Abstract: This article presents a comprehensive review of lithium as a strategic resource, specifically in the production of batteries for electric vehicles. This study examines global lithium reserves, extraction sources, purification processes, and emerging technologies such as direct lithium extraction methods. This paper also explores the environmental and social impacts of lithium extraction, emphasizing the need for sustainable and ethical practices within the supply chain. As electric vehicles are projected to account for over 60% of new car sales by 2030, the demand for high-performance batteries will persist, with lithium playing a key role in this transition, even with the development of alternatives to lithium-ion batteries, such as sodium and ammonium-based technologies. However, there is an urgent need for technological advancements to reduce the environmental impact of lithium production and lithium-ion battery manufacturing. Additionally, ensuring the safety of LiBs during both use and recycling stages is critical to sustainable EV adoption. This study concludes that advancements in battery recycling and the development of new technologies are essential to improving safety, reducing costs, and minimizing environmental impacts, thereby securing a sustainable lithium supply and supporting the future of electric mobility.

Keywords: lithium extraction; electric vehicles; sustainable supply chain; battery recycling; lithium-ion batteries

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1. Introduction

The transition to electric mobility is a reality to which our society must adapt. Electromobility adoption is considered one of the most promising and necessary strategies to meet global decarbonization goals [1,2]. In Europe, the sale of internal combustion engine vehicles (ICEV) is projected to end in 2030 [3]. Globally, the transition to electromobility is anticipated to begin with the sale of hybrid cars (HEV), followed by plug-in hybrids (PHEV), and finally, full electric vehicles (EVs) [4]. The third decade of the 21st century is critical for migrating from ICEV to electric technologies [5–7].

Currently, most automotive brands offer at least one EV option; some have even ceased the production of ICEV [8,9]. Sales of EVs increased by 975% between 2012 and 2017 and are estimated to account for 30% of the total market by 2030 [10]. Lithium-ion batteries (LiBs) are critical for the advancement of EV technologies, as they offer significant advantages over other types of batteries. Additionally, their ability to effectively integrate with renewable energy sources, such as solar and wind power, enhances the reliability and performance of EVs [11]. However, the expansion of the LiB market and their large-scale adoption in the automotive sector are significantly constrained by challenges related to their safety performance. In response to these issues, stringent safety standards and testing protocols have been established to evaluate battery behavior and influential factors to meet the required safety demands [12]. In essence, our work provides an in-depth examination of the critical role lithium plays in electric mobility, emphasizing its relevance in energy storage technologies while also addressing the safety considerations essential for their widespread adoption and underscoring its importance for a more sustainable society.

Lithium has a wide range of industrial and technological applications owing to its chemical and physical properties. Its main applications include ceramics and glass, greases and lubricants, metal alloys, and medical industries, as well as nuclear power generation and battery production. Lithium's demand has risen sharply over the past decade, promoted primarily by the production of batteries, energy storage technologies, and EVs.

By 2030, the projections indicate that the Li_2CO_3 demand will reach 4 million tons. This represents a 700% increase compared to 2021, highlighting the growing importance of this material. Additionally, by 2023, the demand for lithium-ion batteries used in EVs, energy storage systems, electric bikes, tools, and other portable devices could reach 4500 gigawatt-hours (GWh) [13]. This emphasizes the central role that lithium-ion batteries play in meeting the rising energy needs across multiple sectors.

From 2000 to 2017, the growth in battery demand averaged 20% per year, and it is estimated to be duplicated during the 2018–2028 period [14–16]. By 2030, forecasts suggest that the demand for batteries will be 5.5 times higher than in 2018 [17]. This increase in demand is driven by the expected global fleet of 300 million EVs by 2030, which would account for more than 60% of new car sales, a significant increase compared to the 4.6% share they represented in 2020 [18,19]. Although lithium applications differ by region, global end uses during 2023 have been estimated as follows: 87% for batteries, 4% for ceramics and glass, 2% for lubricating greases, 1% for air treatment, 1% for continuous casting mold flux powders, 1% for medical purposes, and 4% for other uses, as shown in Figure 1 [20]. However, the substitution of lithium compounds is feasible in several sectors, including batteries, ceramics, greases, and manufactured glass, but it requires an exhaustive evaluation.

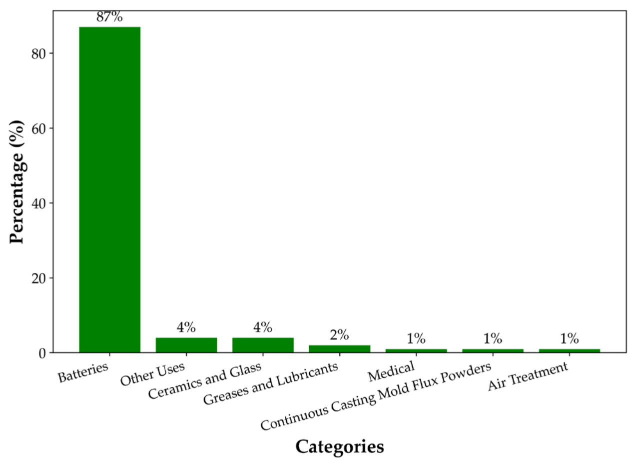

Figure 1. 2023's Lithium applications (created by the author with data from [20]).

Since lithium is a strategic resource, it could face a potential supply crisis in the near future [21]. In this comprehensive review, we take an in-depth look at the impact of this resource on the transition to sustainable electric mobility. Our main purpose is to clarify the fundamental role of the lithium industry in future scenarios and facilitate a sustainable integration of EVs into society. This paper includes a detailed analysis of the lithium extraction sources and purification processes, as well as an assessment of the current and projected supply. We also explore the implications that the growing EV market will have on the demand and management of this resource.

The development of this work was supported by key references from the existing literature on lithium extraction, availability, and future prospects. The references used in this study were sourced from established academic databases, ensuring a wide selection of high-quality, peer-reviewed literature. Publications from 2010 onward were included to ensure that the research is based on the most relevant and up-to-date information. Notably, Meng et al. [21] offered a broad understanding of lithium's role across various industries. Martin et al. [15] provided important insights into the global supply, future demand, and pricing trends. Additionally, Chen et al. [22] were essential in addressing the critical safety issues related to battery lifecycle management and recycling. These studies were fundamental in shaping the analysis and conclusions presented in this work.

The purpose of this paper is to analyze the relationship between lithium, the industries involved in battery production for EVs, and the impact of sustainable management of this resource on future prospects. The main aim is to generate positive changes that facilitate an effective transition to electromobility. To do this, we pose key research questions: Are current lithium resources sufficient to support the development of a global EV fleet in the future? What are the tangible impacts associated with the production of lithium-ion batteries? Are there emerging battery technologies that could displace lithium in EV applications in the near future?

2. Global Lithium Reserves and Availability

For the automotive industry, lithium is a key resource, particularly in the context of the rising adoption of EVs. The geographical distribution of lithium reserves globally has direct implications on the battery supply chain and on the industry's availability to meet EV demand. In this section, we examine the global distribution of lithium reserves, highlighting the key regions that contribute to the supply chain. In addition, the geopolitical and economic dynamics that could influence the availability and access to lithium are analyzed, as well as critical aspects for the development and sustainable expansion of the automotive industry in the future.

Lithium, in its pure metallic form, is not available in nature due to its high reactivity with oxygen, nitrogen, and water vapor present in the atmosphere [23]. Therefore, it is mainly obtained from conventional deposits such as brines, pegmatites like spodumene, and sedimentary deposits [24], which are detailed in Sections 2.1–2.3. Additionally, unconventional sources are examined in Section 2.4. As resource exploration continues, proven lithium deposits will increase, reaching 105 million tons in 2023 [20].

Figure 2 shows the global distribution of lithium reserves by country. Additionally, it highlights the leading countries in lithium reserves, with Bolivia, Argentina, and Chile holding the largest shares, collectively representing over 50% of the world's known reserves. The resource distribution is crucial, as the types of deposits such as brines, spodumene, and clay have a direct impact on the extraction methods, economic feasibility, and environmental implications. Countries like Australia, China, and Germany also play significant roles in the global supply chain, helping to fulfill the growing demand for lithium-based compounds [20].

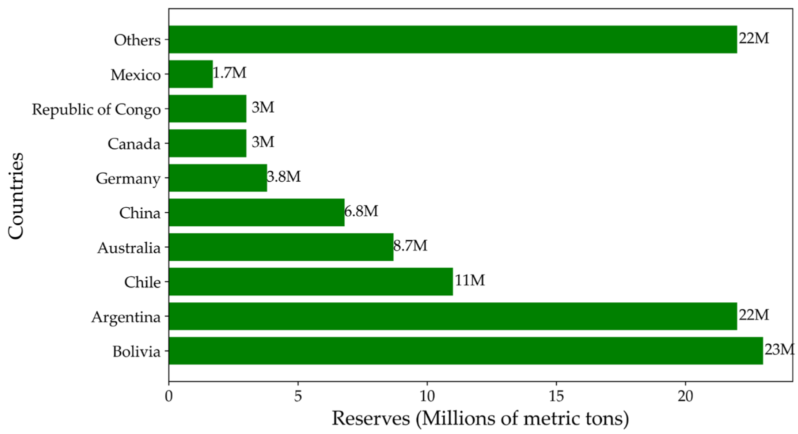

Figure 2. Worldwide lithium reserves (created by the author with data from [20]).

Globally, around 66% of the world's lithium reserves are found in brine deposits, especially in the Lithium Triangle of South America, constituted by Argentina, Bolivia, and Chile. Pegmatite deposits contribute about 30% of reserves, with Australia being the leading producer of lithium from these sources, particularly in the Greenbushes mine. Meanwhile, clay sources, which make up around 4% of the global reserves, are being actively explored for future mining potential, especially in the U.S. and Mexico [25].

2.1. Lithium Brine Deposits

Lithium brine deposits are the largest and cheapest source for lithium production [26]. These deposits are formed over millions of years by a complex combination of geological processes [27]. Brine formations represent between 66% and 78% of the world's lithium resources, mainly concentrated in the region known as the "lithium triangle", constituted by Argentina, Chile, and Bolivia, with an approximate area of 4000 km^2 [28–30]. Moreover, significant deposits have been identified on the Tibetan Plateau as well as in Nevada, United States [31,32]. Nonetheless, efficient lithium production from brines requires specific conditions such as low rainfall, a high evaporation rate, and elevations above 2000 m above sea level. The Atacama salt flat in Chile meets all of the above specifications, making it an exceptional case for lithium production [33].

2.2. Lithium Pegmatite Deposits

Hard rock deposits encompass various styles of lithium mineralization in sedimentary and magmatic rocks like spodumene. These formations can contain a wide variety of lithium-bearing minerals such as micas, pyroxenes, silicates, and phosphates [34]. Significant pegmatite resources, mainly spodumenes, have been found in Australia, the United States, Canada, the Democratic Republic of Congo, China, Russia, Brazil, India, Austria, Portugal, Ireland, Finland, and Italy [34–37]. Among these, the Cinovec deposit, located amidst the Czech Republic and Germany, is the largest known deposit of pegmatites in Europe [38]. Historically, lithium production from pegmatite deposits has been dominated by Australia, particularly by the Greenbushes deposit [29,34].

2.3. Lithium Sedimentary Deposits

To meet the growing demand for lithium, new sources need to be explored beyond conventional resources, such as sedimentary deposits and clays [39]. These sedimentary deposits are classified into various types, including hectorite, illite–smectite mixtures, jadarite, and deep-sea sediments [23,40]. In countries such as Serbia, China, Tanzania, and Mexico, important sedimentary resources with the potential to be exploited have been identified [24,40–43]. It is essential to continue with extensive screening in the area to sustain the increase in demand, especially in the context of sustainable electromobility. In Section 2.4, we review the new important prospects that could provide a lithium supply in the future.

2.4. New Potential Lithium Sources

This section examines various promising prospects for lithium extraction with the aim of strengthening the supply chain and driving the sustainable development of the automotive industry. Nowadays, the use of geophysical, geochemical, and remote sensing techniques, as well as the sampling of sediments from streams, have made it possible to identify potential sources of lithium [44–47]. For instance, lithium sedimentary resources have been detected in Canada, with concentrations ranging from 0.488 ppm to 3.840 ppm [48]. In Malaysia, coastal sediments have concentrations of 21.84 ppm to 146.22 ppm [49]. In addition, marine resources in the Pacific Ocean between the coasts of Mexico and Hawaii are estimated to be around 2.8 million tons of lithium [50].

Likewise, lithium has been reported in mud and water samples from volcanoes in Japan and Indonesia [51]. Exploration of lithium resources in groundwater has also been documented [52]. Concentrations up to 185 ppm and 710 ppm, respectively, have been found in coal basins in Illinois and Inner Mongolia [53,54]. Marine black shale, oil fields, and geothermal waste are lithium carriers that have a possibility of exploration [55,56]. Some nations are even considering exploiting extraterrestrial bodies as potential reserves of metal, including lithium, to meet future requirements [57]. Nevertheless, the incorporation of all these new sources of lithium is currently limited due to the low concentrations present in these resources [58]. Although lithium extraction technologies have improved in efficiency, it is necessary to continue advancement in this area to make the exploitation of these unconventional resources viable. Despite the current challenges, considering these alternative sources is crucial owing to the potential that they have to contribute to the correct adoption of electromobility, particularly in the case of a supply crisis due to strategic and political issues such as those to which Bolivia and Chile are susceptible [59,60].

Despite this, meeting the growing demand for lithium is a significant challenge. Even nowadays, there is an ongoing debate about whether the current supply can support a future global fleet of EVs and other uses. Contrastingly, long-term estimates suggest that by 2100, global lithium production could reach 39 million tons, while the maximum projected demand is around 20 million tons [29]. This indicates that even with rapid EV adoption, lithium resources are unlikely to pose a supply risk in the near future. In addition, it is important to note that recycling LiBs at the end of their life could further ease supply concerns, helping to meet the demand more effectively.

3. Extraction and Processing Technologies

Lithium extraction processing and technologies have come under extensive evaluation in recent years, powered mostly by the growing demand for this essential resource in the manufacturing of batteries for electric vehicles and other electronic devices. This section analyzes the existing and emerging methodologies for lithium extraction, evaluating their feasibility, environmental impact, and associated costs for their application in energy storage technologies.

Every type of lithium resource, indistinctly of whether it is brine, pegmatite, or sediment, requires a specific processing approach directly related to the particular specifications of the source deposit. For brine, lithium concentrations start between 100–1000 ppm. Through evaporation, these concentrations increase to 6000 ppm, making the brine suitable for further processing. Direct lithium extraction method (DLE) technologies, such as ion exchange or adsorption, can elevate the lithium concentrations much faster than solar evaporation. This is followed by the refining methods, such as precipitation or ion exchange, to produce lithium hydroxide or carbonate. In spodumene ore, the lithium content varies from 0.5% to 1.5%. After crushing and concentrating the ore, it is roasted with sulfuric acid and leached. The resulting solution undergoes additional refining to achieve high-purity lithium products suitable for battery-grade applications [61].

Most of the pegmatitic resources extracted in Australia are processed in China to obtain lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH), as they are essential compounds for battery production [43]. For the recovery of lithium from pegmatites, various unit operations and processes are used, such as leaching, liquid–solid extraction, ion exchange, calcining, physical screening, and sieving, as well as magnetic, hydrostatic, electromagnetic, and electrostatic separation methods [23]. The most commonly employed techniques for spodumene processing are dense media separation (DMS) and foam flotation [62]. Techniques using H_2SO_4 and NaOH are also reported in the literature [63]. Spodumene in its natural form (α-form) is compact and difficult to leach, but with proper pretreatment, it becomes a more reactive form (β-form), making it easier to leach [64,65]. Usually, after various operations, Li_2CO_3 is obtained as a main product [66].

Lithium recovery from brines is more economical compared to spodumene or sediment extraction. As a result, the majority of the world's lithium production comes from brine sources. In contrast, there are several factors that slow down lithium production from brine, such as slow production and the large areas required for evaporation ponds in traditional processing. The natural evaporation process of brines takes 10 to 24 months to complete [67]. Furthermore, the presence of other minerals such as Mg, Na, K, and Ca can negatively affect the recovery efficiency and quality of the lithium obtained. Despite these challenges, important advances have been made in the development of innovative technologies for the efficient separation and extraction of lithium from brines, allowing a faster, more adaptable, and efficient process. These efficiency enhancements are crucial to ensuring a steady and sustainable supply of lithium that can meet the growing demands of the technology and automotive industry.

Among the lithium extraction methods, DLE is the most popular. These methods have numerous advantages, including the elimination of evaporation ponds and the reduction of purification time. Implementing DLE technologies, the production of lithium from brine becomes a controllable process that can be adapted to fluctuations in global demand. The DLE techniques are divided into three main categories, which we synthesized in Table 1.

Table 1. DLE categories.

Categories	Articles
Adsorption	Reich et al. [68,69] Ding et al. [70] Necke et al. [71] Paranthaman et al. [72] Kölbel et al. [73]
Ion Exchange	Li et al. [74,75] Liu et al. [76] Zandevakili et al. [77]
Solvent Extraction	Zhang et al. [78] Song et al. [79]

Lithium extraction from sedimentary sources uses unit processes similar to spodumene processing. Specifically for lithium recovery in clays, calcination methods with gypsum and lime, followed by selective chlorination or water leaching, are usually preferred [52]. Acidification methods are especially effective for extracting lithium from clay minerals, standing out for their low energy consumption and high efficiency [55,80].

The cost and feasibility of the lithium extraction methods depend heavily on local conditions, such as the specific characteristics of the resource deposits and regional energy availability. Methods for lithium extraction vary significantly in terms of resource use, energy consumption, and overall costs. Among these, brine extraction has the lowest cost, between USD 2000 to USD 5000 per ton of Li_2CO_3 [81]. Its main advantages include relatively low energy consumption and resource efficiency, making it the preferred method in regions such as South America.

In contrast, lithium extraction from spodumene is more energy-intensive. The costs range from USD 3000 to USD 6000 per ton of Li_2CO_3 [82]. Despite being more expensive, this method offers faster and more consistent production compared to brine extraction, making it a viable option in regions like Australia. Moreover, extraction from clay involves higher energy demands and is the most costly and complex method, with prices ranging from USD 7000 to USD 10,000 per ton of Li_2CO_3 [81]. Although clay deposits hold considerable lithium potential, the technology for economically extracting lithium from clay is still under development.

Lithium is presented as a promising alternative to facilitate the transition to renewable energies and electromobility. Its automotive industry application has the ability to reduce dependence on fossil fuels. However, this mineral presents significant environmental challenges that require attention [38]. Lithium mining, extraction, and processing processes are crucial factors that need to be addressed to ensure their long-term sustainability. Intensive lithium harvesting has major sustainability consequences at the production stage [80].

Lithium extraction from spodumene is significantly more environmentally aggressive compared to brine extraction. Reports indicate that depending on the type of spodumene, the environmental footprint can be 9.3 to 60.4 times greater than that of brine extraction. This is due to the high energy demands and intensive chemical inputs in processing this mineral. This highlights the importance of evaluating the environmental impacts as the lithium demand continues to rise, especially considering the trend towards increased solid mineral extraction, like spodumene, rather than the more sustainable brine sources [25]. Mining operations in arid lands such as the Salar de Atacama have shown negative impacts on the region's ecology, local fauna, and the way of life of surrounding communities [83–86]. In addition, the intensive consumption of water by these activities can reach up to 65% of the available water resources in the region, compromising the supply of the basic needs of the communities in the area [87,88].

Food security is also affected by lithium mining, first because of the high water consumption and second due to the crops near the extraction area suffering effects on their growth and yield [89–91]. The production of 1 ton of Li_2CO_3 from brine requires 15.5–32.8 m^3 of fresh water, while the production of LiOH requires 31–50 m^3; in comparison, production from concentrated ore requires 77 and 69 m^3 for the production of Li_2CO_3 and LiOH, respectively [92]. To alleviate these effects, several DLE processes have been developed to enable the recovery of lithium salts and the production of up to 500 m^3 of fresh water per ton of Li_2CO_3 [16,93,94]. The performance in water recovery depends on the extraction zone and is inversely proportional to the total dissolved solids (TDS). The water retrieval rates range from 0.102 to 0.397 kg of fresh water per kg of virgin brine [67].

Most DLE technologies employ variants of reverse osmosis or seawater reverse osmosis (SWRO), as well as flash distillation and pretreatments such as membrane crystallization (MCr). Existing SWRO plants consume 3–4 kWh/m^3 of fresh water, produced with associated CO_2 emissions of 1.4–1.8 $kgCO_2/m^3$ and a cost of 0.31–0.95 USD/m^3 [93]. The implementation of these technologies shows the ability to settle some of the problems associated with lithium production and, in turn, boost the production of lithium-ion batteries.

The current research on lithium extraction focuses on improving efficiency, reducing environmental impacts, and utilizing all potential sources from which lithium can be extracted. Key advancements include the development of DLE technologies, which use selective adsorption or electrochemical methods. These techniques allow for lithium extraction from diluted sources such as seawater, geothermal brines, or even wastewater from shale gas production. Furthermore, they are faster and more energy-efficient compared to traditional evaporation processes.

In addition, research on advanced materials, such as titanium-based sieves, is being reported to improve lithium recovery from brines. Another line of investigation focuses on enhancing lithium recovery from spodumene. In this sense, current studies aim to optimize the roasting and leaching processes to reduce energy consumption and minimize environmental damage [61].

4. Lithium-Ion Battery Technology in Electric Vehicles

A rechargeable lithium-ion battery generates electricity by moving ions between the anode and cathode. These batteries consist of four main components: the anode, cathode, electrolyte, and separator. EVs now offer performance, comfort, and technology comparable to or superior to ICEVs due in large part to the development of lithium-ion batteries. At the beginning of the last decade, these batteries faced limitations such as reduced power in cold regions and a short lifespan of around 5 years [29].

Over the past decade, as EVs emerged as a viable alternative, limitations in their charging capacity and performance were prevalent. The primary motivation for this paper is the critical need to evaluate lithium for battery production to ensure optimal performance and sustainability in this swiftly developing industry. Initially, the available batteries offered capacities of 40 kWh with a maximum performance of 200 km [29]. Nowadays, the HEV, PHEV, and EV feature average battery capacities of 2 kWh, 15 kWh, and 75 kWh, respectively. Additionally, technological advances have led to improved efficiencies, with reported yields of 5 kWh/100 km for the HEV, 3.5 kWh/100 km for the PHEV, and 15.56 kWh/100 km for the EV [95]. This allows the EV to match the ICEV in terms of performance, although areas that require development still remain.

EV features, such as the ability to recharge at home or at commercial charging stations, promote their adoption compared to fuel cell electric vehicles (FCEVs), which require more complex infrastructure to be able to recharge [96]. However, one of the main challenges to the widespread adoption of EVs is their charging time. While Tesla's superchargers allow an EV to recharge to 80% in 30 min, the total charging time is still significantly longer than the time it takes to refuel an ICEV. Therefore, the spend-charging capability of various electrode materials in lithium-ion batteries has recently been comprehensively reviewed [97]. Important expectations in this field have been developed; for example, the manufacture of a battery that recharges in 1 min to travel 800 km is intended [98].

Recently, more accessible and easier alternatives to lithium-ion batteries, such as solid sodium batteries, have been developed [99]. A further option is ammonium-ion-based batteries, which implies using inexpensive and widely available raw materials [100]. These batteries have a lower freezing point, making them suitable for use in regions with cold climates [101]. Furthermore, the use of metals that are more affordable than lithium, such as Cr, Mn, and Na, has been reported [102]. Hydrogen ion fuel cells are also emerging as a promising alternative for use in FCEVs. Nonetheless, despite the potential, all these technologies are still in the early development phases compared to lithium. For the time being, the viable alternatives for the automotive industry continue to be those based on lithium, so improvements in this technology continue to be explored and developed. For instance, lithium–sulfur batteries are capable of storing more energy than traditional lithium-ion batteries and are seen as a significant step towards greater energy efficiency in the future [103].

With the quick growth of the lithium-ion battery market for electric vehicles, it is crucial to review the environmental impact associated with their production. Several life cycle assessments have evaluated the impact of different battery alternatives on the automotive sector [10,104–106]. Recycling has been identified as essential to reduce the environmental impact and mitigate uncertainty about lithium availability [107,108]. Nevertheless, lithium recycling has not been optimized due to its high cost compared to the value of lithium [108–111]. This sector could supply between 50% and 63% of the cumulative demand between 2010 and 2100 [29]. To develop efficient recycling processes, it is crucial to know the composition of the batteries and overcome the limitations associated with disassembly. In 2023, approximately 40 companies in Canada and the United States, as well as 50 companies in Europe, were involved in lithium battery recycling or planned to do so [20]. However, the recycling techniques must be accompanied by policies on the subject to be available in the future [107].

5. Challenges and Environmental Considerations

The extraction and processing of lithium for the automotive industry face significant environmental, safety, economic, and social challenges. Since the mining of lithium is water-intensive, especially in arid regions, its overuse can destabilize local ecosystems and impact community lifestyle [112].

The mining of lithium, which may cause chemical pollution, releases elements such as arsenic, boron, and magnesium into the environment, infiltrating local water sources and harming human health and wildlife. Steward et al. [113] highlighted the need to better manage and mitigate harmful practices, as they have documented the presence of these dangerous elements in water bodies surrounding mining operation areas.

Mining operations also lead to the destruction of natural habitats and the loss of biodiversity, which severely affects the ecosystem. Olivetti et al. [114] mentioned that mining activities affect endemic species and disrupt the ecological balance, causing long-lasting consequences for regional biodiversity.

The production of lithium batteries, as well as their extraction, processing, and manufacturing, generate GHG and CO_2 emissions, thus significantly affecting the environmental benefits of EVs [115]. In the manufacturing of lithium batteries, it was found that polyethylene has the most significant impact, requiring 580 MJ and 40 kg of CO_2 eq per kilogram due to the high energy demand in the production process. NCM (nickel cobalt manganese oxide), NCA (nickel cobalt aluminum oxide), and CNT (carbon nanotubes) also play an important role, requiring around 400 MJ/kg and emitting 30 kg of CO_2 eq. It can be observed that greenhouse gas emissions would be 69% to 92% higher to meet the material demands for the same lithium-ion battery cell capacity if the materials were manufactured in China instead of the United States [116]. This highlights the importance of optimizing production processes and supply chains to minimize the environmental impact and promote sustainability in the growing demand for lithium-based energy storage.

Economically speaking, the lithium supply chain faces numerous challenges, as price volatility and the reduced geographic concentration of lithium reserves create supply uncertainties. The instability in the demand for EVs and the evolution of lithium-ion battery technologies considerably impact the lithium market. Relying on only a few countries for most of the global lithium production can result in geopolitical and economic risks as well as compromise the achievement of global environmental goals.

These challenges will be addressed by adopting sustainable and ethical approaches in the lithium supply chain, such as DLE and direct lithium to product (DLP), both being more efficient and less environmentally detrimental extraction technologies. DLE and DLP have the potential to increase the efficiency of lithium recovery, reduce their water use, and minimize the environmental footprint of mining operations [112].

Most lithium production takes place in Latin America, Australia, and Asia, yet Europe, North America, Brazil, and Africa are also regions to be explored and developed in an attempt to diversify lithium sources. This strategy can ensure a more stable and sustainable supply of lithium as well as help mitigate the risks associated with geographic concentration [114].

Improvement in lithium battery recycling practices must become a primary focus of the industry, as battery recycling (which is still in its early stages) has the potential to provide the industry with a significant source of lithium for the future. The growth of the recycling rates and the development of more efficient technologies in the recovery of lithium from used batteries will lower the demand for virgin lithium, thus reducing the environmental impacts of mining operations [113].

Transparency and accountability in the lithium supply chain are also important, as mining operations must not only meet strict environmental and social standards but also benefit, as much as possible, the local communities. Partnerships between governments, companies, and non-governmental organizations (NGOs) can help develop regulatory frameworks and policies to promote sustainable, safe, and ethical practices in lithium mining [114].

Safety Hazards in Lithium-Ion Batteries

As previously mentioned, LiBs have a broad range of applications; however, safety concerns significantly limit their scalability for future uses. In particular, the deployment of LiBs in EVs is challenged by their safety performance limitations [117,118]. Over the past few years, numerous LiBs have been recalled from the market following incidents involving explosions and fires [119,120]. This is still a very serious problem, as there are fires in electric vehicles almost every week around the world [121]. These failures have not only resulted in considerable economic losses across the affected industries but have also severely tarnished the reputation of LiBs as a reliable energy storage system [122]. As a result, Chen et al. [121] presented several tests to assess the quality and safety of these batteries, including overcharge, heating, short circuit, internal short circuit, nail penetration, and crush tests. In the safety assessments derived from these test outcomes, EUCAR and SAE-J hazard levels are widely applied. Nonetheless, the safety and stability of the LiB's performance can be significantly improved by carefully selecting electrode materials, separators, and electrolytes, as well as optimizing the battery's design.

Thus, the safety of LiBs is largely determined by their chemical composition, as well as the operating environment and operating conditions [123]. Typically, the LiB consists of four main components: the cathode, anode, separator, and electrolyte [124]. A malfunction in any of these components, individually or collectively, can negatively impact its safety. If any component becomes damaged, the battery can transition from controlled electrochemical reactions to uncontrolled ones, resulting in significant heat generation [125].

During battery operation, a considerable amount of heat is produced, and if there is no efficient dissipation route, this heat can cause the battery to overheat, severely compromising its safety [121]. Additionally, there are various types of cells used in the LiB, such as cylindrical, prismatic, coin, and pouch cells, which are often arranged in parallel or in a series to create a battery pack with a specific voltage and capacity [126]. For instance, the Tesla EVs contain approximately 7000 cylindrical cells, delivering a total voltage of 400 V and a capacity of 85 kWh [127]. Despite this, managing such a large battery pack poses significant challenges for ensuring battery safety.

Thermal runaway is one of the most critical safety issues in LiBs, along with secondary reactions involving the electrolyte, cathode, anode, and interfacial reactions in the electrode surfaces and lithium plating. These secondary reactions are often caused by mechanical, thermal, or electrical abuse. There are five primary causes of this phenomenon: uncontrollable internal heat generation, separator defects, electrical abuse, electrochemical side reactions due to localized thermal stress, and mechanical damage to the battery, which can cause short circuits or allow air to infiltrate the battery [121]. Among these categories, the leading causes of battery safety incidents are short circuits resulting from separator damage, electrical abuse, and mechanical abuse [118].

There are internal and external strategies to improve battery safety. The former strategies focus on enhancing the components themselves, such as using more stable materials and additives that improve electrolyte safety by preventing adverse effects. On the other hand, external strategies include incorporating cooling systems that help maintain stable temperatures, thereby reducing the likelihood of thermal runaway [128]. Additionally, safety standards and testing methods have been developed to ensure that LiBs and their components meet specified safety criteria, especially in commercial applications [121].

Moreover, the risks associated with the improper disposal of LiBs after their end-of-life are significant. WMW (2021) [129] reported that nearly 40% of forest fires in the United Kingdom were caused by the incorrect disposal of LiBs. These incidents not only pose serious environmental hazards but also have significant economic consequences for the countries where these batteries are manufactured and used [22]. In addition, recycling LiBs is particularly challenging due to the inherent safety risks involved in handling and processing them. Therefore, it is crucial to develop a safe and efficient process for the dismantling and recycling of LiBs to mitigate these risks and minimize their environmental harm [130].

The safety challenges associated with lithium-ion batteries, both during their operation and after their useful life, present issues that must be addressed through comprehensive strategies. The development of advanced materials, improved design methodologies, and enhanced battery management systems are crucial to reducing the frequency of incidents like thermal runaway and ensuring future large-scale applications of LiBs, particularly in EVs.

6. Market Dynamics and Industry Applications

Since 2015, China has been the world's largest EV market, prompting the growth of the LiB market as well. LiBs, an essential component in the production of EVs, are directly influenced by government policies and economic incentives.

Tesla, BYD, and NIO are some of the major EV manufacturing companies that are expanding the EV market in China, which greatly depends on the production of LiBs. Tesla models such as the Model 3, for example, with advanced battery technology and a robust charging network, have shown remarkable performance in the EV market [131].

The market performance of EV models with lithium-ion batteries has been generally positive. The BYD Tang EV, for example, has seen a significant increase in its sales due to its energy efficiency and extended range. This increase is directly attributed to its use of high-capacity LiBs [132].

China's strict policies have been instrumental in the adoption of EVs and in the growing demand for LiBs. These measures have significantly increased the demand for lithium in the automotive industry [133]. The Chinese government has also implemented subsidies for EV purchases and has set targets to reduce CO_2 emissions. Furthermore, as the EV charging infrastructure continues to expand, the EV market also grows, making EVs more appealing to consumers [134].

The evolution of the NCM 111 battery to the NCM 811 battery has significantly decreased the LiB's environmental impact. These newer and more improved batteries use a greater amount of nickel while diminishing their cobalt and manganese use, thus reducing their CO_2 emissions and their non-renewable energy consumption. This change not only improves battery efficiency but also reduces manufacturing costs [135].

Although it is known that the recycling of used LiBs significantly reduces their environmental impact, their recycling numbers remain low, making this a significant challenge to overcome within the industry. In China, it is estimated that only 30% of discarded LiBs are correctly recycled, limiting their environmental and economic benefits [136]. Improving the recycling rate is important to establishing a sustainable and efficient recycling industry.

The cost of producing LiBs significantly impacts the overall cost of EVs. The average cost of lithium-ion battery packs dropped 89%, from USD 1100 to USD 137 per kilowatt-hour (kWh) in the period 2010–2020. However, despite this substantial decrease, the cost of battery packs still accounts for a significant portion of an EV's total cost, ranging from 30% to 40%, depending on the vehicle's size and battery capacity [137]. Furthermore, while the reduction in battery prices is a positive development for EV affordability, the shift toward more sustainable, recyclable, and less resource-intensive battery technologies remains a priority.

In LIBs, the commercialization of new chemicals that partially replace Co with Ni has occurred faster than expected [138]. As the amount of cobalt in more recent batteries decreases, so too does the profitability of LiB recycling. Nevertheless, LiB recycling remains profitable, with an average profit of USD 412 to USD 738 per battery. The decrease in the amount of recyclable cobalt poses an economic challenge for the future [139]. Circular economy strategies are required to reduce reliance on primary resources and enhance the resilience and sustainability of automotive supply chains [140].

7. LiBs Reuse and Recycling for Sustainable Electric Mobility

The growing adoption of EVs highlights the importance of repurposing their batteries for non-automotive applications to reduce their environmental impact [141]. This section explores innovative uses for EV batteries once they no longer meet vehicle efficiency requirements. Various strategies have been developed to optimize the life cycle of these batteries. In this context, recycling is emerging as a key solution, having a significant impact on the battery manufacturing industry in leading countries such as China and South Korea [142–146].

It is expected that LiBs will continue to dominate the automotive industry in the coming decades, at least until their competitors overcome challenges related to efficiency, reliability, and durability [147,148]. Battery manufacturers commonly offer warranties of around 8 years for LiBs, while the average lifespan of an EV is about 15 years [149]. However, due to factors such as high costs and limited incentives to replace batteries, it is unlikely they will be replaced before the EV reaches the end of its lifespan, even as efficiency declines [150–152].

Despite uncertainty regarding the efficiency loss of LiBs, their lifespan in secondary applications is estimated to reach 10 years, with a maximum projected lifespan of up to 20 years [150,153–155]. The reuse and recycling of LiBs offer various benefits, such as extending their lifespan, recovering valuable materials like Li and Co, and reducing hazardous waste such as Cd and Pb [156,157].

Few studies have modeled the usage phase of LiBs in stationary second-life applications using monitored data [158]. Most evaluations of LiBs focus on residential storage applications [158–161]. However, the energy and environmental benefits of repurposing batteries in energy storage systems combined with renewable energy generation technologies have been assessed, demonstrating significant contributions [162]. Battery degradation during both the first- and second-life phases is a key factor in determining feasibility and longevity in secondary applications [158]. Nonetheless, this remains a topic that requires ongoing, thorough research [163–166].

Less demanding applications in terms of efficiency, such as energy storage for residential buildings or communication base stations, are promising alternatives for the use of batteries from EVs [162,167,168]. A replaced EV battery still retains between 70% and 80% of its initial capacity [154,158]. Therefore, its implementation in secondary activities, such as in the construction sector, is a viable option [169]. However, it is recommended that once the battery's capacity falls below 60%, recycling should be considered to maintain reliability and promote a circular economy mechanism [155,170]. In fact, the reuse of used batteries in secondary applications in buildings could help improve the environmental impact of electric mobility.

The global market for LiB recycling is expected to reach USD 11 billion by 2027 [171]. The amount of end-of-life LiBs generated, primarily from EVs, is projected to reach 1336.5 GWh by 2040 [172]. Economically, remanufacturing LiBs offers a 40% cost saving compared to producing batteries from virgin materials [173]. Recycling, for instance, can reduce manufacturing costs by 25.6% to 36.6%, water consumption by 30.1% to 41.2%, and greenhouse gas emissions by 29.3% to 38.2%. However, safety remains a key challenge for large-scale LiB applications in the industry [22].

To process and recycle the increasing number of batteries reaching the end of their lifecycle, it is projected that recycling capacity will need to increase by up to 45 times by 2050 compared to the capacity available in 2021 [140,174]. In this context, the reuse of LiBs in secondary applications not only benefits electric mobility but also drives the development of more efficient recycling technologies. Extending the battery's lifespan through reuse alleviates pressure on recycling systems, allowing industrial capacities to adapt gradually. Additionally, it fosters innovation in material recovery techniques, optimizing both the sustainability and profitability of recycling processes.

8. Conclusions and Future Perspectives

Lithium, a key resource in the EV industry, plays a pivotal role in the development of LiBs, as LiBs benefit greatly from lithium's unique properties. Their high energy density and their ability to remain charged for extended periods make LiBs the core of energy storage technology in EVs.

These features have not only allowed EVs to compete with internal combustion vehicles but have also eased their expansion into the electric transportation market.

The studies reviewed in this article stress that lithium significantly contributes to mitigating GHG emissions, as the use of LiBs reduces dependence on fossil fuels and decreases the carbon footprint associated with internal combustion vehicles. As the energy efficiency and range of lithium batteries continue to improve, EVs will become a more viable alternative to conventional cars.

LiBs will continue to be widely used in the coming years due to their unique energy density and efficiency, making them central to the evolution of EVs. As EVs become a more viable alternative to conventional vehicles, the demand for high-performance batteries will persist, with lithium playing a key role in driving this transition. Although challenges related to lithium extraction and environmental impact remain, advancements in technology, such as solid-state batteries, promise to enhance the sustainability and efficiency of lithium-ion technology. Additionally, ongoing research into battery recycling and the reuse of lithium resources will play a critical role in reducing pressure on the lithium reserves. As long as technological innovations and responsible resource management are prioritized, lithium will remain a crucial component in the future of clean energy and sustainable transportation.

Nevertheless, the use of lithium in the EV industry comes with its own challenges. The extraction and processing processes of lithium can negatively impact the environment as the demand for lithium reserves increases. These issues highlight the need to address not only lithium's availability but also the extraction and recycling practices to ensure that lithium is used responsibly and resourcefully.

Technological advancements and resource management strategies make lithium a key component in EV batteries for the foreseeable future, as battery innovations will play a crucial role in the evolution of the industry. Solid-state batteries, one of the most promising elements among emerging technologies, use a solid electrolyte instead of liquid as conventional lithium-ion batteries do. The use of a solid electrolyte offers higher energy density, improved safety, and a longer life cycle. This improvement reduces the need for lithium and other materials while improving battery performance and sustainability [175].

The ability to recover and reuse lithium and other valuable materials at the end of their battery life is an important area that must be developed in order to minimize pressure on the lithium reserves as well as its environmental impacts. Recycling techniques, such as hydrometallurgical recycling and pyrometallurgical recycling, are constantly evolving, improving efficiency and reducing costs. To ensure a sustainable supply chain for lithium, more investment in advanced recycling technologies and recycling infrastructure needs to take place.

Reusing LiBs is a key strategy that needs to be looked at deeply. The application of these strategies makes it possible to extend the useful life of batteries, contributing to the sustainable development of society. Less performance-demanding applications, such as storing energy from renewable sources for use in homes or businesses, represent a promising option for reuse.

Additionally, to support the sustainability of lithium, it is also necessary to evaluate the logistics of electric vehicle assembly, enabling designs that facilitate disassembly after their useful life to allow for the reuse of lithium batteries. However, this aspect falls outside the scope of this current research.

At present, research to find alternatives to complement or replace lithium in applications is being conducted. Sodium and magnesium are some of the materials being mentioned as solutions to reduce dependence on lithium, which could diversify the available energy storage options.

To ensure a sustainable lithium supply chain, both resource management and technological innovations must be addressed as a comprehensive approach. Below are several key suggestions for stakeholders in the automotive industry [176]:

- **Promote Research and Development (R&D) in Extraction and Processing Technologies:** Industry stakeholders should invest in R&D to improve the extraction methods and to reduce the environmental impact. The development of less intrusive extraction techniques, such as lithium extraction from brines, which is a more sustainable alternative to traditional mining, is an ideal option.
- **Promote Battery Recycling:** The implementation of policies and investment in infrastructure is essential to ensure that valuable materials can be properly recycled. Initiatives to standardize and optimize recycling processes can increase the recovery rate and reduce the costs associated with recycling.
- **Establish Strategic Partnerships:** Cooperation between manufacturers, lithium suppliers, and government authorities can help create a regulatory framework to promote sustainability in the supply chain. Public and private partnerships will promote sustainable practices and implement innovative technologies.
- **Implement Sustainability Policies and Certification:** Governments and international organizations should implement policies that support sustainability. Grants

for responsible mining practices and compliance with environmental regulations will ensure that lithium is obtained ethically and sustainably.

- **Educate and Raise Awareness among Stakeholders:** It is critical to educate all participants involved on the importance of a sustainable lithium supply chain. Awareness can encourage the adoption of responsible practices, and it will compel consumers to demand ethically manufactured products.

Lithium, undoubtedly, is a key component in the transition to a more sustainable form of transportation. However, to accelerate the adoption of EVs, it is crucial for decision-makers to implement economic incentives that make these cars more accessible. Such incentives would not only reduce the initial cost but also encourage investment in charging infrastructure, thereby facilitating a faster transition to more sustainable and efficient transportation. As the demand for EVs grows, the need to protect the environment and ensure the future availability of lithium is a challenge that must be faced head-on. To ensure that lithium continues to be an essential component in the development of a more sustainable and cleaner future, technological innovations and responsible management practices will be required to meet this challenge. Merging technological innovations, effective policies, and a cooperative association between industries and manufacturers will create a path toward a lithium supply chain that is both efficient and environmentally friendly.

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References

1. International Energy Agency. *Net Zero by 2050: A Roadmap for the Global Energy Sector*; International Energy Agency: Paris, France, 2021.
2. United Nations Framework Convention on Climate Change. *Paris Agreement*; United Nations: New York, NY, USA, 2015.
3. *EU Must End New Petrol and Diesel Car Sales by 2030 to Meet Climate Targets—Report*; The Guardian: London, UK, 2018.
4. Brown, S.; Pyke, D.; Steenhof, P. Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy* **2010**, *38*, 3797–3806. [CrossRef]
5. Sperling, D. Electric vehicles: Approaching the tipping point. *Bull. At. Sci.* **2018**, *74*, 11–18. [CrossRef]
6. Mazur, C.; Offer, G.; Contestabile, M.; Brandon, N. Comparing the effects of vehicle automation, policy-making and changed user preferences on the uptake of electric cars and emissions from transport. *Sustainability* **2018**, *10*, 676. [CrossRef]
7. Parker, D. The ascendency of electric motive power as a gradual replacement for the internal combustion engine (ICE), 'Ockham's Electric Razor. *Int. J. Environ. Stud.* **2018**, *75*, 532–536. [CrossRef]
8. Volvo Cars Global Media Newsroom. *Volvo Cars to Go All Electric*; Volvo Car Corporation: Gothenburg, Sweden, 2017.
9. Vaughan, A. *Jaguar Land Rover to Make Only Electric or Hybrid Cars from 2020*; The Guardian: London, UK, 2017.
10. Dai, Q.; Kelly, J.C.; Gaines, L.; Wang, M. Life cycle analysis of lithium-ion batteries for automotive applications. *Batteries* **2019**, *5*, 48. [CrossRef]
11. Lowe, M.; Tokuoka, S.; Trigg, T.; Gereffi, G. *Lithium-Ion Batteries for Electric Vehicles: The U.S. Value Chain*; Contributing CGGC Researcher: Ansam Abayechi; Duke University Center on Globalization, Governance & Competitiveness: Durham, NC, USA, 2010.
12. *GB/T 31485-2015*; Safety Requirements and Test Methods for Traction Battery of Electric Vehicle. Road Vehicles: Tianjin, China, 2015. (In English)

13. Azevedo, M.; BaczyÅska, M.; Hoffman, K.; Krauze, A. *Lithium Mining: How New Production Technologies Could Fuel the Global EV Revolution*; McKinsey & Company: Brussels, Belgium, 2022.
14. Liu, W.; Agusdinata, D.B. Interdependencies of lithium mining and communities sustainability in Salar de Atacama, Chile. *J. Clean. Prod.* **2010**, *260*, 120838. [CrossRef]
15. Martin, G.; Rentsch, L.; Höck, M.; Bertau, M. Lithium market research—Global supply, future demand and price development. *Energy Storage Mater.* **2017**, *6*, 171–179. [CrossRef]
16. Flexer, V.; Baspineiro, C.F.; Galli, C.I. Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Sci. Total Environ.* **2018**, *639*, 1188–1204. [CrossRef]
17. Sakunai, T.; Ito, L.; Tokai, A. Environmental impact assessment on production and material supply stages of lithium-ion batteries with increasing demands for electric vehicles. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 470–479. [CrossRef]
18. Swain, B. Recovery and recycling of lithium: A review. *Sep. Purif. Technol.* **2017**, *172*, 388–403. [CrossRef]
19. Obaya, M.; Mauricio, C. *Análisis de las Redes Globales de Producción de Baterías de Ion de Litio: Implicaciones para los Países del Triángulo del Litio*; Comisión Económica para América Latina y el Caribe: Santiago, Chile, 2021.
20. Mineral Commodity Summaries. U.S. Geological Survey Publications Warehouse: Washington, DC, USA, 2024.
21. Meng, F.; McNeice, J.; Zadeh, S.S.; Ghahreman, A. review of lithium production and recovery from minerals, brines, and lithium-ion batteries. *Miner. Process. Extr. Metall. Rev.* **2019**, *42*, 123–141. [CrossRef]
22. Chen, Z.; Yildizbasi, A.; Wang, Y.; Sarkis, J. Safety Concerns for the Management of End-of-Life Lithium-Ion Batteries. *Glob. Chall.* **2022**, *6*, 2200049. [CrossRef] [PubMed]
23. Balaram, V.; Santosh, M.; Satyanarayanan, M.; Srinivas, N.; Gupta, H. Lithium: A review of applications, occurrence, exploration, extraction, recycling, analysis, and environmental impact. *Geosci. Front.* **2024**, *15*, 101868. [CrossRef]
24. Stephenson, L. Tectonic related lithium deposits another major region found north east Tanzania—A new area with close association to the dominant areas: The fourth of four. *Nat. Resour.* **2023**, *14*, 161–191. [CrossRef]
25. Hard Rock Lithium, vs. *Brine—How Do Their Carbon Curves Compare?* Benchmark Source: London, UK, 2023.
26. Yaksic, A.; Tilton, J.E. Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium. *Resour. Policy* **2009**, *34*, 185–194. [CrossRef]
27. Munk, L.A.; Hynek, S.A.; Bradley, D.C.; Boutt, D.; Labay, K.; Jochens, H. Lithium brines: A global perspective. In *Rare Earth and Critical Elements in Ore Deposits*; Society of Economic Geologists: Littleton, CO, USA, 2016.
28. Kaya, M. State-of-the-art lithium-ion battery recycling technologies. *Circ. Econ.* **2022**, *1*, 100015. [CrossRef]
29. Gruber, P.W.; Medina, P.A.; Keoleian, G.A.; Kesler, S.E.; Everson, M.P.; Wallington, T.J. Global lithium availability. *J. Ind. Ecol.* **2011**, *15*, 760–775. [CrossRef]
30. Szlugaj, J.; Radwanek-Bąk, B. Lithium sources and their current use. *Gospod. Surowcami Miner.-Miner. Resour. Manag.* **2023**, *31*, 61–88.
31. Xue, F.; Tan, H.; Zhang, X.; Santosh, M.; Cong, P.; Ge, L.; Li, C.; Chen, G.; Zhang, Y. Contrasting sources and enrichment mechanisms in lithium-rich salt lakes: A Li-H-O isotopic and geochemical study from northern Tibetan Plateau. *Geosci. Front.* **2023**, *15*, 101768. [CrossRef]
32. Parker, S.S.; Franklin, B.; Williams, A.; Cohen, B.S.; Clifford, M.; Rohde, M.M. *Potential Lithium Extraction in the United States: Environmental, Economic, and Policy Implications*; The Nature Conservancy: Arlington, VA, USA, 2022.
33. Al-Jawad, J.; Ford, J.; Petavratzi, E.; Hughes, A. Understanding the spatial variation in lithium concentration of high Andean Salars using diagnostic factors. *Sci. Total Environ.* **2023**, *906*, 167647. [CrossRef]
34. Gourcerol, B.; Gloaguen, E.; Melleton, J.; Tuduri, J.; Galiegue, X. Re-assessing the European lithium resource potential—A review of hard-rock resources and metallogeny. *Ore Geol. Rev.* **2019**, *109*, 494–519. [CrossRef]
35. Keyser, W.; Müller, A.; Steiner, R.; Erambert, M.; Kristoffersen, M.; Unterweissacher, T. Alpine eclogite-facies modification of Li-Cs-Ta pegmatite from the Wolfsberg lithium deposit, Austria. *Miner. Depos.* **2023**, *58*, 1191–1210. [CrossRef]
36. Zhang, H.; Tian, S.; Wang, D.; Li, X.; Liu, T.; Zhang, Y.; Fu, X.; Hao, X.; Hou, K.; Zhao, Y.; et al. Lithium isotope behavior during magmatic differentiation and fluid exsolution in the Jiajika granite–pegmatite deposit, Sichuan, China. *Ore Geol. Rev.* **2021**, *134*, 104139. [CrossRef]
37. Dini, A.; Lattanzi, P.; Ruggieri, G.; Trumpy, E. Lithium Occurrence in Italy—An Overview. *Minerals* **2022**, *12*, 945. [CrossRef]
38. Toupal, J.; Vann, D.R.; Zhu, C.; Gieré, R. Geochemistry of surface waters around four hard-rock lithium deposits in Central Europe. *J. Geochem. Explor.* **2022**, *234*, 106937. [CrossRef]
39. Garcia, L.V.; Ho, Y.-C.; Myo Thant, M.M.; Han, D.S.; Lim, J.W. Lithium in a sustainable circular economy: A comprehensive review. *Processes* **2023**, *11*, 418. [CrossRef]
40. Hein, J.R.; Koschinsky, A.; Kuhn, T. Deep-ocean polymetallic nodules as a resource for critical materials. *Nat. Rev. Earth Environ.* **2020**, *1*, 158–169. [CrossRef]
41. Stefanović, N.; Danilović Hristić, N.; Petrić, J. Spatial planning, environmental activism, and politics—Case study of the Jadar project for lithium exploitation in Serbia. *Sustainability* **2023**, *15*, 1736. [CrossRef]
42. Li, C.; Li, Z.; Wu, T.; Luo, Y.; Zhao, J.; Li, X.; Yang, W.; Chen, X. Metallogenic characteristics and formation mechanism of naomugeng clay-type lithium deposit in Central Inner Mongolia, China. *Minerals* **2021**, *11*, 238. [CrossRef]
43. Kramer, D. Fears of a lithium supply crunch may be overblown. *Phys. Today* **2021**, *74*, 20–22. [CrossRef]

44. Cao, H.-W.; Pei, Q.-M.; Santosh, M.; Li, G.-M.; Zhang, L.-K.; Zhang, X.-F.; Zhang, Y.-H.; Zou, H.; Dai, Z.-W.; Lin, B.; et al. Himalayan leucogranites: A review of geochemical and isotopic characteristics, timing of formation, genesis, and rare metal mineralization. *Earth-Sci. Rev.* **2022**, *234*, 104229. [CrossRef]
45. Galliski, M.Á.; Márquez-Zavalía, M.F.; Roda-Robles, E.; von Quadt, A. The Li-bearing pegmatites from the Pampean Pegmatite Province, Argentina: Metallogenesis and Resources. *Minerals* **2022**, *12*, 841. [CrossRef]
46. Ding, T.; Zheng, M.; Peng, S.; Lin, Y.; Zhang, X.; Li, M. Lithium extraction from salt lakes with different hydrochemical types in the Tibet Plateau. *Geosci. Front.* **2022**, *14*, 101485. [CrossRef]
47. van de Ven, M.; Gazley, M.; Sterk, R.; Aldrich, S.; Werner, E. Exploration for lithium-caesium-tantalum (LCT) pegmatites in New Zealand. In Proceedings of the Conference Paper New Zealand Minerals Forum, Hamilton, ON, Canada, 13–14 October 2020; pp. 87–91.
48. Nicolas, M.P.B. Preliminary investigation of the potential for lithium in groundwater in sedimentary rocks in southwestern Manitoba. In *Report of Activities 2017*; Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey: Reed Lake, MB, Canada, 2017; pp. 183–190.
49. Cheng, H.; Zakaria, M.; Aris, A.Z.; Tan, S. Lithium levels in peninsular Malaysian Coastal Areas: An assessment based on mangrove Snail Nerita lineata and surface sediments. *Pertanika J. Trop. Agric. Sci.* **2015**, *38*, 1–10.
50. Hein, J.R.; Mizell, K.; Koschinsky, A.; Conrad, T.A. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geol. Rev.* **2013**, *51*, 1–14. [CrossRef]
51. Sari, N.A.; Warmada, I.W.; Anggara, F. The potential of lithium enrichment in lapindo brantas, mount anyar, and buncitan mud volcanoes, sidoarjo district, east java province. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *851*, 012040. [CrossRef]
52. Dugamin, E.J.M.; Cathelineau, M.; Boiron, M.-C.; Richard, A.; Despinois, F. Lithium enrichment processes in sedimentary formation waters. *Chem. Geol.* **2023**, *635*, 121626. [CrossRef]
53. Zhang, W.; Noble, A.; Yang, X.; Honaker, R. Lithium leaching recovery and mechanisms from density fractions of an Illinois Basin bituminous coal. *Fuel* **2020**, *268*, 117319. [CrossRef]
54. Sun, Y.; Li, Y.; Zhao, C.; Lin, M.; Wang, J.; Qin, S. Concentrations of lithium in Chinese coals. *Energy Explor. Exploit.* **2010**, *28*, 97–104. [CrossRef]
55. Zhao, H.; Ling, K.; Qin, S.; Lei, M.; Wen, H. Modes of occurrence of lithium in black shale in the Nandan area, Guangxi, SW China: Implications for clay-type resources. *Ore Geol. Rev.* **2023**, *157*, 105409. [CrossRef]
56. Mends, E.A.; Chu, P. Lithium extraction from unconventional aqueous resources—A review on recent technological development for seawater and geothermal brines. *J. Environ. Chem. Eng.* **2023**, *11*, 110710. [CrossRef]
57. Dallas, J.A.; Raval, S.; Saydam, S.; Dempster, A.G. Investigating extraterrestrial bodies as a source of critical minerals for renewable energy technology. *Acta Astronaut.* **2021**, *186*, 74–86. [CrossRef]
58. Dang, C.; Helal, A.S.; Zhu, L.; Xu, G.; Zhu, M. Industrial pathways to lithium extraction from seawater: Challenges and perspectives. *Nano Res. Energy* **2023**, *2*, e9120059. [CrossRef]
59. Telsnig, T.; Potz, C.; Hass, J.; Eltrop, L.; Palma-Behnke, R. Opportunities to integrate solar technologies into the Chilean lithium mining industry—Reducing process related GHG emissions of a strategic storage resource. *AIP Conf. Proc.* **2017**, *1850*, 110017.
60. Vara, A.M. A South American approach to metamorphosis as a horizon of equality: Focusing on controversies over lithium. *Curr. Sociol.* **2014**, *63*, 100–104. [CrossRef]
61. Alera, A.C.; Benitez, J.P.; Fernandez, R.J.; Pascual, C.K.; Policarpio, F.; Lopez, E.C.R. Recent Advances in Lithium Extraction. *Eng. Procedings* **2024**, *67*, 52. [CrossRef]
62. Kundu, T.; Rath, S.S.; Das, S.K.; Parhi, P.K.; Angadi, S.I. Recovery of lithium from spodumene-bearing pegmatites: A comprehensive review on geological reserves, beneficiation, and extraction. *Powder Technol.* **2023**, *415*, 118142. [CrossRef]
63. Gao, T.; Fan, N.; Dai, T. Lithium extraction from hard rock lithium ores: Technology, resources, environment and cost. *China Geol.* **2022**, *6*, 137–153.
64. Guo, H.; Kuang, G.; Wang, H.; Yu, H.; Zhao, X. Investigation of enhanced leaching of lithium from α-spodumene using hydrofluoric and sulfuric acid. *Minerals* **2017**, *7*, 205. [CrossRef]
65. Fosu, A.Y.; Kanari, N.; Vaughan, J.; Chagnes, A. Literature review and thermodynamic modelling of roasting processes for lithium extraction from spodumene. *Metals* **2020**, *10*, 1312. [CrossRef]
66. Margarido, F.; Vieceli, N.; Durão, F.; Guimarães, C.; Nogueira, C.A. Minerometallurgical processes for lithium recovery from pegmatitic ores. *Comun. Geológicas* **2014**, *101*, 795–798.
67. Baspineiro, C.F.; Franco, J.; Flexer, V. Potential water recovery during lithium mining from high salinity brines. *Sci. Total Environ.* **2020**, *720*, 137523. [CrossRef] [PubMed]
68. Reich, R.; Slunitschek, K.; Danisi, R.M.; Eiche, E.; Kolb, J. Lithium extraction techniques and the application potential of different sorbents for lithium recovery from brines. *Miner. Process. Extr. Metall. Rev.* **2022**, *44*, 261–280. [CrossRef]
69. Reich, R.; Danisi, R.M.; Kluge, T.; Eiche, E.; Kolb, J. Structural and compositional variation of zeolite 13X in lithium sorption experiments using synthetic solutions and geothermal brine. *Microporous Mesoporous Mater.* **2023**, *359*, 112623. [CrossRef]
70. Ding, T.; Zheng, M.; Peng, S.; Nie, Z.; Lin, Y.; Wu, Q. Recovery of lithium ions from salt lakes using nanofibers containing zeolite carriers. *Front. Energy Res.* **2022**, *10*, 895681. [CrossRef]
71. Necke, T.; Stein, J.; Kleebe, H.-J.; Balke-Grünewald, B. Lithium extraction and zeolite synthesis via mechanochemical treatment of the silicate minerals lepidolite, spodumene, and petalite. *Minerals* **2023**, *13*, 1030. [CrossRef]

72. Paranthaman, M.P.; Li, L.; Luo, J.; Hoke, T.; Ucar, H.; Moyer, B.A.; Harrison, S. Recovery of lithium from geothermal brine with lithium–aluminum layered double hydroxide chloride sorbents. *Environ. Sci. Technol.* **2017**, *51*, 13481–13486. [CrossRef]
73. Kölbel, L.; Kölbel, T.; Herrmann, L.; Kaymakci, E.; Ghergut, I.; Poirel, A.; Schneider, J. Lithium extraction from geothermal brines in the Upper Rhine Graben: A case study of potential and current state of the art. *Hydrometallurgy* **2023**, *221*, 106131. [CrossRef]
74. Li, H.; Eksteen, J.; Kuang, G. Recovery of lithium from mineral resources: State-of-the-art and perspectives—A review. *Hydrometallurgy* **2019**, *189*, 105129. [CrossRef]
75. Li, X.; Mo, Y.; Qing, W.; Shao, S.; Tang, C.Y.; Li, J. Membrane-based technologies for lithium recovery from water lithium resources: A review. *J. Membr. Sci.* **2019**, *591*, 117317. [CrossRef]
76. Liu, J.; Zhang, Y.; Miao, Y.; Yang, Y.; Li, P. Alkaline resins enhancing li^+/h^+ ion exchange for lithium recovery from brines using granular titanium-type lithium ion-sieves. *Ind. Eng. Chem. Res.* **2021**, *60*, 16457–16468. [CrossRef]
77. Zandevakili, S.; Ranjbar, M.; Ehteshamzadeh, M. Recovery of lithium from Urmia Lake by a nanostructure MnO_2 ion sieve. *Hydrometallurgy* **2014**, *149*, 148–152. [CrossRef]
78. Yang, S.; Liu, G.; Wang, J.; Cui, L.; Chen, Y. Recovery of lithium from alkaline brine by solvent extraction with functionalized ionic liquid. *Fluid Phase Equilibria* **2019**, *493*, 129–136. [CrossRef]
79. Song, J.; Nghiem, L.D.; Li, X.; He, T. Lithium extraction from Chinese salt-lake brines: Opportunities, challenges, and future outlook. *Environ. Sci. Water Res. Technol.* **2017**, *3*, 593–597. [CrossRef]
80. Zhao, H.; Wang, Y.; Cheng, H. Recent advances in lithium extraction from lithium-bearing clay minerals. *Hydrometallurgy* **2023**, *217*, 106025. [CrossRef]
81. S&P Global Market Intelligence. *Essential Insights: Lithium Costs & Margins*; Market Intelligence | S&P Global: New York, NY, USA, 2019.
82. *The Battle between Spodumene and Brine—Lithium Mining*; Essential Intelligence S&P Global: New York, NY, USA, 2024.
83. Adeel, M.; Zain, M.; Shakoor, N.; Ahmad, M.A.; Azeem, I.; Aziz, M.A.; Tulcan, R.X.S.; Rathore, A.; Tahir, M.; Horton, R.; et al. Global navigation of lithium in water bodies and emerging human health crisis. *NPJ Clean Water* **2023**, *6*, 33. [CrossRef]
84. Moran, B.J.; Boutt, D.F.; McKnight, S.V.; Jenckes, J.; Munk, L.A.; Corkran, D.; Kirshen, A. Relic groundwater and prolonged drought confound interpretations of water sustainability and lithium extraction in arid lands. *Earth's Future* **2022**, *10*, e2021EF002555. [CrossRef]
85. Kavanagh, L.; Keohane, J.; Cleary, J.; Garcia Cbellos, G.; Lleoyd, A. Lithium in the natural waters of the south east of Ireland. *Int. J. Environ. Res. Public Health* **2017**, *14*, 561. [CrossRef]
86. Gutiérrez, J.S.; Moore, J.N.; Donnelly, J.P.; Dorador, C.; Navedo, J.G.; Senner, N.R. Climate change and lithium mining influence flamingo abundance in the Lithium Triangle. *Proc. R. Soc. B Biol. Sci.* **2022**, *289*, 20212388. [CrossRef]
87. Wanger, T.C. The Lithium future-resources, recycling, and the environment. *Conserv. Lett.* **2011**, *4*, 202–206. [CrossRef]
88. Katwala, A. *The Spiraling Environmental Cost of Our Lithium Battery Addiction*; Wired Energy: Boone, IA, USA, 2018; pp. 1–15.
89. Vera, M.L.; Torres, W.R.; Galli, C.I.; Chagnes, A.; Flexer, V. Environmental impact of direct lithium extraction from brines. *Nat. Rev. Earth Environ.* **2023**, *4*, 149–165. [CrossRef]
90. Bolan, N.; Hoang, S.A.; Tanveer, M.; Wang, L.; Bolan, S.; Sooriyakumar, P.; Robinson, B.; Wijesekara, H.; Wijesooriya, M.; Keerthanan, S.; et al. From mine to mind and mobiles—Lithium contamination and its risk management. *Environ. Pollut.* **2021**, *290*, 118067. [CrossRef] [PubMed]
91. Shahzad, B.; Tanveer, M.; Hassan, W.; Shah, A.N.; Anjum, S.A.; Cheema, S.A.; Ali, I. Lithium toxicity in plants: Reasons, mechanisms and remediation possibilities—A review. *Plant Physiol. Biochem.* **2016**, *107*, 104–115. [CrossRef] [PubMed]
92. Kelly, J.C.; Wang, M.; Dai, Q.; Winjobi, O. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium-ion battery cathodes and lithium-ion batteries. *Resour. Conserv. Recycl.* **2021**, *174*, 105762. [CrossRef]
93. Macedonio, F.; Drioli, E. Chap. 6: Advanced membrane-based desalination systems for water and minerals extracted from the sea. In *Desalination Sustainability a Technical, Socioeconomic, and Environmental Approach*; Elsevier: Amsterdam, The Netherlands, 2017.
94. Ling, Z.; Shi, C.; Li, F.; Fu, Y.; Zhao, J.; Dong, H.; Yang, Y.; Zhou, H.; Wang, S.; Song, Y. Desalination and Li+ enrichment via formation of cyclopentane hydrate. *Sep. Purif. Technol.* **2020**, *231*, 115921. [CrossRef]
95. Wang, R.; Song, Y.; Xu, H.; Li, Y.; Liu, J. Life cycle assessment of energy consumption and CO_2 emission from HEV, PHEV and BEV for China in the past, present and future. *Energies* **2022**, *15*, 6853. [CrossRef]
96. Eftekhari, A. Lithium batteries for electric vehicles: From economy to research strategy. *ACS Sustain. Chem. Eng.* **2019**, *7*, 5602–5613. [CrossRef]
97. Eftekhari, A. Lithium-Ion batteries with high-rate capabilities. *ACS Sustain. Chem. Eng.* **2017**, *5*, 2799–2816. [CrossRef]
98. Wisner, M. *Fisker Patents Car Battery with 500-Mile Range on a Minute's Charge*; Fox Business: New York, NY, USA, 2017.
99. Chi, X.; Zhang, Y.; Hao, F.; Kmiec, S.; Dong, H.; Xu, R.; Zhao, K.; Ai, Q.; Terlier, T.; Wang, L.; et al. An electrochemically stable homogeneous glassy electrolyte formed at room temperature for all-solid-state sodium batteries. *Nat. Commun.* **2022**, *13*, 2854. [CrossRef]
100. Wang, Y.; Kuchena, S.F. Recent progress in aqueous ammonium-ion batteries. *ACS Omega* **2022**, *7*, 33732–33748. [CrossRef]
101. Zheng, M.-P.; Xing, E.-Y.; Zhang, X.-F.; Li, M.-M.; Che, D.; Bu, L.-Z.; Han, J.-H.; Ye, C.-Y. Classification and mineralization of global lithium deposits and lithium extraction technologies for exogenetic lithium deposits. *China Geol.* **2023**, *6*, 547–566.

102. Kawaguchi, T.; Bian, X.; Hatakeyama, T.; Li, H.; Ichitsubo, T. Influences of enhanced entropy in layered rocksalt oxide cathodes for lithium-ion batteries. *ACS Appl. Energy Mater.* **2022**, *5*, 4369–4381. [CrossRef]
103. Nakamura, N.; Ahn, S.; Momma, T.; Osaka, T. Future potential for lithium-sulfur batteries. *J. Power Sources* **2023**, *558*, 232566. [CrossRef]
104. Notter, D.A.; Gauch, M.; Widmer, R.; Wäger, P.; Stamp, A.; Zah, R.; Althaus, H.-J. Contribution of li-ion batteries to the environmental impact of electric vehicles. *Environ. Sci. Technol.* **2010**, *44*, 6550–6556. [CrossRef] [PubMed]
105. Majeau-Bettez, G.; Hawkins, T.R.; Strømman, A.H. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ. Sci. Technol.* **2011**, *45*, 4548–4554. [CrossRef]
106. Dunn, J.; Gaines, L.; Barnes, M.; Sullivan, J.; Wang, M. *Material and Energy Flows in the Materials Production, Assembly and End of Life Stages of the Automotive Lithium-Ion Battery Life Cycle*; Energy Systems Division: Oak Ridge, TN, USA, 2012.
107. Kushnir, D.; Sandén, B.A. The time dimension and lithium resource constraints for electric vehicles. *Resour. Policy* **2012**, *37*, 93–103. [CrossRef]
108. Liu, C.; Lin, J.; Cao, H.; Zhang, Y.; Sun, Z. Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review. *J. Clean. Prod* **2019**, *228*, 801–813. [CrossRef]
109. Heelan, J.; Gratz, E.; Zheng, Z.; Wang, Q.; Chen, M.; Apelian, D.; Wang, Y. Current and prospective li-ion battery recycling and recovery processes. *JOM* **2016**, *68*, 2632–2638. [CrossRef]
110. Ordoñez, J.; Gago, E.J.; Girard, A. Processes and technologies for the recycling and recovery of spent lithium-ion batteries. *Renew. Sustain. Energy Rev.* **2016**, *60*, 195–205. [CrossRef]
111. Zeng, X.; Li, J.; Singh, N. Recycling of spent lithium-ion battery: A critical review. *Crit. Rev. Environ. Sci. Technol.* **2014**, *44*, 1129–1165. [CrossRef]
112. Agusdinata, D.B.; Liu, W.; Eakin, H.; Romero, H. Socio-environmental impacts of lithium mineral extraction: Towards a research agenda. *Environ. Res. Lett.* **2018**, *13*, 123001. [CrossRef]
113. Steward, D.; Mayyas, A.; Mann, M. Economics and challenges of Li-ion battery recycling from end-of-life vehicles. *Procedia Manuf.* **2019**, *33*, 272–279. [CrossRef]
114. Olivetti, E.A.; Ceder, G.; Gaustad, G.G.; Fu, X. Lithium-ion battery supply chain considerations: Analysis of potential bottlenecks in critical metals. *Joule* **2017**, *1*, 229–243. [CrossRef]
115. Celadon, A.; Sun, H.; Sun, S.; Zhang, G. Batteries for electric vehicles: Technical advancements, environmental challenges, and market perspectives. *SusMat* **2024**, e234. [CrossRef]
116. Yin, R.; Hu, S.; Yang, Y. Life cycle inventories of the commonly used materials for lithium-ion batteries in China. *J. Clean. Prod.* **2019**, *227*, 960–971. [CrossRef]
117. Love, C.T.; Buesser, C.; Johannes, M.D.; Swider-Lyons, K.E. Innovating Safe Lithium-Ion Batteries Through Basic to Applied Research. *J. Electrochem. Energy Convers. Storage* **2017**, *15*, 011006. [CrossRef]
118. Feng, X.; Ouyang, M.; Liu, X.; Lu, L.; Xia, Y.; He, X. Thermal runaway mechanism of lithium-ion battery for electric vehicles: A review. *Energy Storage Mater.* **2018**, *10*, 246–267. [CrossRef]
119. Finegan, D.P.; Scheel, M.; Robinson, J.B.; Tjaden, B.; Hunt, I.; Mason, T.J.; Millichamp, J.; Di Michiel, M.; Offer, G.J.; Hinds, G.; et al. In-operando high-speed tomography of lithium-ion batteries during thermal runaway. *Nat. Commun.* **2015**, *6*, 6924. [CrossRef]
120. Chen, Z.; Xiong, R.; Lu, J.; Li, X. Temperature rise prediction of lithium-ion battery suffering external short circuit for all-climate electric vehicles application. *Appl. Energy* **2018**, *213*, 375–383. [CrossRef]
121. Chen, Y.; Kang, Y.; Zhao, Y.; Wang, L.; Liu, J.; Li, Y.; Liang, Z.; He, X.; Li, X.; Tavajohi, N.; et al. A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards. *J. Energy Chem.* **2021**, *59*, 83–99. [CrossRef]
122. Williard, N.; He, W.; Hendricks, C.; Pecht, M. Lessons learned from the 787 dreamliner issue on lithium-ion battery reliability. *Energies* **2013**, *6*, 4682–4695. [CrossRef]
123. Zhao, Q.; Guo, Z.; Wu, Y.; Wang, L.; Han, Z.; Ma, X.; Zhu, Y.; Cao, C. Hierarchical flower-like spinel manganese-based oxide nanosheets for high-performance lithium-ion battery. *Sci. China Mater.* **2019**, *62*, 1385–1392. [CrossRef]
124. Dunn, B.; Kamath, H.; Tarascon, J.M. Electrical Energy Storage for the Grid: A Battery of Choices. *Science* **2011**, *334*, 928–935. [CrossRef] [PubMed]
125. Liu, X.; Ren, D.; Hsu, H.; Feng, X.; Xu, G.-L.; Zhuang, M.; Gao, H.; Lu, L.; Han, X.; Chu, Z.; et al. Thermal Runaway of Lithium-Ion Batteries without Internal Short Circuit. *Joule* **2018**, *2*, 2047–2064. [CrossRef]
126. Tarascon, J.M.; Armand, M. Issues and challenges facing rechargeable lithium batteries. *Nature* **2001**, *414*, 359–367. [CrossRef]
127. Winter, M.; Barnett, B.; Xu, K. Before li ion batteries. *Chem. Rev.* **2018**, *118*, 11433–11456. [CrossRef]
128. Chen, D.; Jiang, J.; Kim, G.-H.; Yang, C.; Pesaran, A. Comparison of different cooling methods for lithium-ion battery cells. *Appl. Therm. Eng.* **2016**, *94*, 846–854. [CrossRef]
129. WMW | Recycling: How to Handle Li-Ion Batteries. WMW. 2021. Available online: https://waste-management-world.com/recycling/how-to-handle-li-ion/ (accessed on 15 June 2024).
130. Marshall, J.; Gastol, D.; Sommerville, R.; Middleton, B.; Goodship, V.; Kendrick, E. Disassembly of Li Ion Cells—Characterization and Safety Considerations of a Recycling Scheme. *Metals* **2020**, *10*, 773. [CrossRef]
131. Weithmann, S. Standardization in China: Electric vehicle technology as driver for change in China's automotive standardization. *Int. J. Stand. Res. (IJSR)* **2016**, *14*, 20–32. [CrossRef]

132. Wang, S.; Yu, J. A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution. *Waste Manag. Res.* **2021**, *39*, 156–164. [CrossRef]
133. Hu, S.; Wen, Z. Why does the informal sector of end-of-life vehicle treatment thrive? A case study of China and lessons for developing countries in motorization process. *Resour. Conserv. Recycl.* **2015**, *95*, 91–99. [CrossRef]
134. Ehsan, F.; Habib, S.; Gulzar, M.M.; Guo, J.; Muyeen, S.M.; Kamwa, I. Assessing policy influence on electric vehicle adoption in China: An in-Depth study. *Energy Strategy Rev.* **2024**, *54*, 101471. [CrossRef]
135. Gaines, L.; Richa, K.; Spangenberger, J. Key issues for Li-ion battery recycling. *MRS Energy Sustain.* **2018**, *5*, E14. [CrossRef]
136. Chatterjee, S. Sustainable electronics waste management in India. In *Paradigm Shift in E-Waste Managemen*; CRC Press: Boca Raton, FL, USA, 2022; pp. 79–106.
137. *Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh | BloombergNEF*; BloombergNEF: New York, NY, USA, 2020.
138. *Electric Vehicle Outlook 2020*; Bloomberg New Energy Finance: New York, NY, USA, 2020.
139. Wang, S.; Yu, J. Evaluating the electric vehicle popularization trend in China after 2020 and its challenges in the recycling industry. *Waste Manag. Res.* **2021**, *39*, 818–827. [CrossRef]
140. Baars, J.; Domenech, T.; Bleischwitz, R.; Melin, H.E.; Heidrich, O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nat. Sustain.* **2020**, *4*, 71–79. [CrossRef]
141. Ricardo Energy & Environment. *Europe's Clean Mobility Outlook: Scenarios for the EU Light-Duty Vehicle Fleet, Associated Energy Needs and Emissions, 2020–2050*; Ricardo Energy & Environment: Didcot, UK, 2018.
142. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **2019**, *575*, 75–86. [CrossRef]
143. Ziemann, S.; Müller, D.B.; Schebek, L.; Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recycl.* **2018**, *133*, 76–85. [CrossRef]
144. Harvey, L.D.D. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. *Appl. Energy* **2018**, *212*, 663–679. [CrossRef]
145. Miedema, J.H.; Moll, H.C. Lithium availability in the EU27 for battery-driven vehicles: The impact of recycling and substitution on the confrontation between supply and demand until 2050. *Resour. Policy* **2013**, *38*, 204–211. [CrossRef]
146. Melin, H.E. *State-of-the-Art in Reuse and Recycling of Lithium-Ion Batteries—A Research Review*; Circular Energy Storage: London, UK, 2019.
147. Vaalma, C.; Buchholz, D.; Weil, M.; Passerini, S. A cost and resource analysis of sodium-ion batteries. *Nat. Rev. Mater.* **2018**, *3*, 18013. [CrossRef]
148. Placke, T.; Kloepsch, R.; Dühnen, S.; Winter, M. Lithium ion, lithium metal, and alternative rechargeable battery technologies: The odyssey for high energy density. *J. Solid-State Electrochem.* **2017**, *21*, 1939–1964. [CrossRef]
149. Dun, G.; Pridmore, A.; Gibson, G.; Kollamthodi, S.; Skinner, I. *Data Gathering and Analysis to Assess the Impact of Mileage on the Cost Efectiveness of the LDV CO_2 Regulation*; Ricardo AEA: Harwell, UK, 2014.
150. Neubauer, J.S.; Smith, K.; Wood, E.; Pesaran, A. *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*; National Renewable Energy Laboratory: Golden, CO, USA, 2015.
151. Saxena, S.; Le Floch, C.; MacDonald, J.; Moura, S. Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models. *J. Power Sources* **2015**, *282*, 265–276. [CrossRef]
152. Zubi, G.; Dufo-López, R.; Carvalho, M.; Pasaoglu, G. The lithium-ion battery: State of the art and future perspectives. *Renew. Sustain. Energy Rev.* **2018**, *89*, 292–308. [CrossRef]
153. Martinez-Laserna, E.; Sarasketa-Zabala, E.; Villarreal Sarria, I.; Stroe, D.-I.; Swierczynski, M.; Warnecke, A.; Timmermans, J.-M.; Goutam, S.; Omar, N.; Rodriguez, P. Technical Viability of Battery Second Life: A Study from the Ageing Perspective. *IEEE Trans. Ind. Appl.* **2018**, *54*, 2703–2713. [CrossRef]
154. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* **2015**, *22*, 111–124. [CrossRef]
155. Casals, L.C.; García, B.A.; Aguesse, F.; Iturrondobeitia, A. Second life of electric vehicle batteries: Relation between materials degradation and environmental impact. *Int. J. Life Cycle Assess.* **2015**, *22*, 82–93. [CrossRef]
156. Bunsen, T.; Cazzola, P.; Gorner, M.; Paoli, L.; Scheffer, S.; Schuitmaker, R.; Tattini, J.; Teter, J. *Global EV Outlook 2018: Towards Cross-Modal Electrification*; IEA: Paris, France, 2018.
157. EU. *Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on Batteries and Accumulators and Waste Batteries and Accumulators and Repealing Directive 91/157/EEC*; OJ L 266 2006; The Stationery Office Limited: London, UK, 2020.
158. Bobba, S.; Mathieux, F.; Ardente, F.; Blengini, G.A.; Cusenza, M.A.; Podias, A.; Pfrang, A. Life Cycle Assessment of repurposed electric vehicle batteries: An adapted method based on modelling energy flows. *J. Energy Storage* **2018**, *19*, 213–225. [CrossRef]
159. Faria, R.; Marques, P.; Garcia, R.; Moura, P.; Freire, F.; Delgado, J.; de Almeida, A.T. Primary and secondary use of electric mobility batteries from a life cycle perspective. *J. Power Sources* **2014**, *262*, 169–177. [CrossRef]
160. Cusenza, M.A.; Bobba, S.; Ardente, F.; Cellura, M.; Di Persio, F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *J. Clean. Prod.* **2019**, *215*, 634–649. [CrossRef]
161. Richa, K.; Babbitt, C.W.; Nenadic, N.G.; Gaustad, G. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int. J. Life Cycle Assess.* **2015**, *22*, 66–81. [CrossRef]

162. Cusenza, M.A.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M. Energy and environmental benefits of circular economy strategies: The case study of reusing used batteries from electric vehicles. *J. Energy Storage* **2019**, *25*, 100845. [CrossRef]
163. Bach, T.C.; Schuster, S.F.; Fleder, E.; Müller, J.; Brand, M.J.; Lorrmann, H.; Jossen, A.; Sextl, G. Nonlinear aging of cylindrical lithium-ion cells linked to heterogeneous compression. *J. Energy Storage* **2016**, *5*, 212–223. [CrossRef]
164. Dubarry, M.; Baure, G.; Pastor-Fernández, C.; Yu, T.F.; Widanage, W.D.; Marco, J. Battery energy storage system modeling: A combined comprehensive approach. *J. Energy Storage* **2019**, *21*, 172–185. [CrossRef]
165. Kabir, M.M.; Demirocak, D.E. Degradation mechanisms in Li-ion batteries: A state-of-the-art review. *Int. J. Energy Res.* **2017**, *41*, 1963–1986. [CrossRef]
166. Liu, Z.; Ivanco, A.; Onori, S. Aging characterization and modeling of nickel-manganese-cobalt lithium-ion batteries for 48V mild hybrid electric vehicle applications. *J. Energy Storage* **2019**, *21*, 519–527. [CrossRef]
167. Yang, J.; Gu, F.; Guo, J. Environmental feasibility of secondary use of electric vehicle lithium-ion batteries in communication base stations. *Resour. Conserv. Recycl.* **2020**, *156*, 104713. [CrossRef]
168. Reid, G.; Julve, J. *Second Life-Batteries as Flexible Storage for Renewables Energies*; Bundesverband Erneuerbare Energie e.V. (BEE): Berlin, Germany, 2016.
169. Hein, R.; Kleindorfer, P.R.; Spinler, S. Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems. *Technol. Forecast. Soc. Change* **2012**, *79*, 1654–1671. [CrossRef]
170. Lacey, G.; Putrus, G.; Salim, A. The use of second life electric vehicle batteries for grid support. In Proceedings of the Eurocon 2013, Zagreb, Croatia, 1–4 July 2013; pp. 1255–1261.
171. Alves, B. *Global Battery Recycling Market Value 2021–2031*; Statista: Hamburg, Germany, 2024.
172. *Amount of Spent Lithium-Ion Batteries from Electric Vehicles and Storage in the Sustainable Development Scenario, 2020–2040*; Charts—Data & Statistics; IEA: Paris, France, 2021.
173. Foster, M.; Isely, P.; Standridge, C.R.; Hasan, M.M. Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. *J. Ind. Eng. Manag.* **2014**, *7*, 698–715. [CrossRef]
174. *Insights—Circular Energy Storage*; Circular Energy Storage: London, UK, 2020.
175. Ehsani, M.; Singh, K.V.; Bansal, H.O.; Mehrjardi, R.T. State of the art and trends in electric and hybrid electric vehicles. *Proc. IEEE* **2021**, *109*, 967–984. [CrossRef]
176. Yu, J.; Wang, S.; Toshiki, K.; Serrona KR, B.; Fan, G.; Erdenedalai, B. Latest trends and new challenges in end-of-life vehicle recycling. In *Environmental Impacts of Road Vehicles: Past, Present and Future*; The Royal Society of Chemistry: Cambridge, UK, 2017; pp. 174–213.