environments

MDPI

Article

Second Life of Used Lithium-Ion Batteries from Electric Vehicles in the USA

Jay Meegoda [1,*], Ghadi Charbel [1] and Daniel Watts [2]

[1] Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA; gc383@njit.edu
[2] Biology Department, Indiana University—Bloomington, Bloomington, IN 47405, USA; dajwatts@indiana.edu
* Correspondence: meegoda@njit.edu; Tel.: +1-973-596-2464

Abstract: This article focuses on the reuse and recycling of end-of-life (EOL) lithium-ion batteries (LIB) in the USA in the context of the rapidly growing electric vehicle (EV) market. Due to the recent increase in the enactment of both current and pending regulations concerning EV battery recycling, this work focuses on the recycling aspect for lithium-ion batteries rather than emphasizing the reuse of EOL batteries (although these practices have value and utility). A comparative analysis of various recycling methods is presented, including hydrometallurgy, pyrometallurgy, direct recycling, and froth flotation. The efficiency and commercial viability of these individual methods are highlighted. This article also emphasizes the practices and capabilities of leading companies, noting their current superior annual processing capacities. The transportation complexities of lithium-ion batteries are also discussed, noting that they are classified as hazardous materials and that stringent safety standards are needed for their handling. The study underscores the importance of recycling in mitigating environmental risks associated with EOL of LIBs and facilitates comparisons among the diverse recycling processes and capacities among key players in the industry.

Keywords: recycling; transportation; safety standards; environmental impact

Citation: Meegoda, J.; Charbel, G.; Watts, D. Second Life of Used Lithium-Ion Batteries from Electric Vehicles in the USA. *Environments* **2024**, *11*, 97. https://doi.org/10.3390/environments11050097

Academic Editor: Ching-Yuan Chang

Received: 11 February 2024
Revised: 4 April 2024
Accepted: 22 April 2024
Published: 7 May 2024

1. Introduction

In the dynamically evolving landscape of battery technology, shaped by the increasing prominence of electric vehicles (EVs), the lifecycle of batteries, especially in applications such as EVs and large-scale energy storage, has emerged as a crucial consideration. With the increased use of EV batteries, aging and deterioration of batteries are inevitable, typically resulting in a functional lifespan of 7 to 20 years. This aging process is driven by factors such as the gradual degradation of electrode materials, loss of active material, and degradation of the electrolyte, leading to reduced battery recharging capacity and efficiency. With EV sales projected to reach 40% of passenger vehicles by 2030 [1,2], addressing the end-of-life management of these batteries becomes increasingly vital, particularly in the United States, where environmental and safety challenges are at the forefront of concern and discussion.

Upon reaching the end of their operational life, either due to aging or due to damage, batteries are replaced at dealerships or body shops. This critical juncture marks the transition to the next phase: transportation to and evaluation at designated collection points. These older batteries are often transported via pallets in trucks, considering their substantial weight and the risks associated with their hazardous nature, so classified due to their thermal, electrical, or chemical properties [3]. At collection points, each battery is assessed for its individual potential path forward: repair, reuse, or recycle. The repair process entails replacing damaged cells within the battery, a process that extends its functional life. While repair is less emphasized in this article, it can be a useful tool in extending the functional lifetime of the battery assembly. It is important to note that the extracted battery cells are typically sent to recycling facilities as well.

Reuse involves repurposing batteries for less demanding applications, maximizing their utility, and postponing the need for recycling. However, when these batteries exhaust their potential in secondary applications, recycling becomes an environmental necessity and a logistical imperative. Recycling allows for the recovery of valuable materials and minerals and reintegrating them into the manufacturing process to produce new batteries, thereby conserving natural resources and reducing the environmental impact of fresh material processing. This journey is represented in Figure 1.

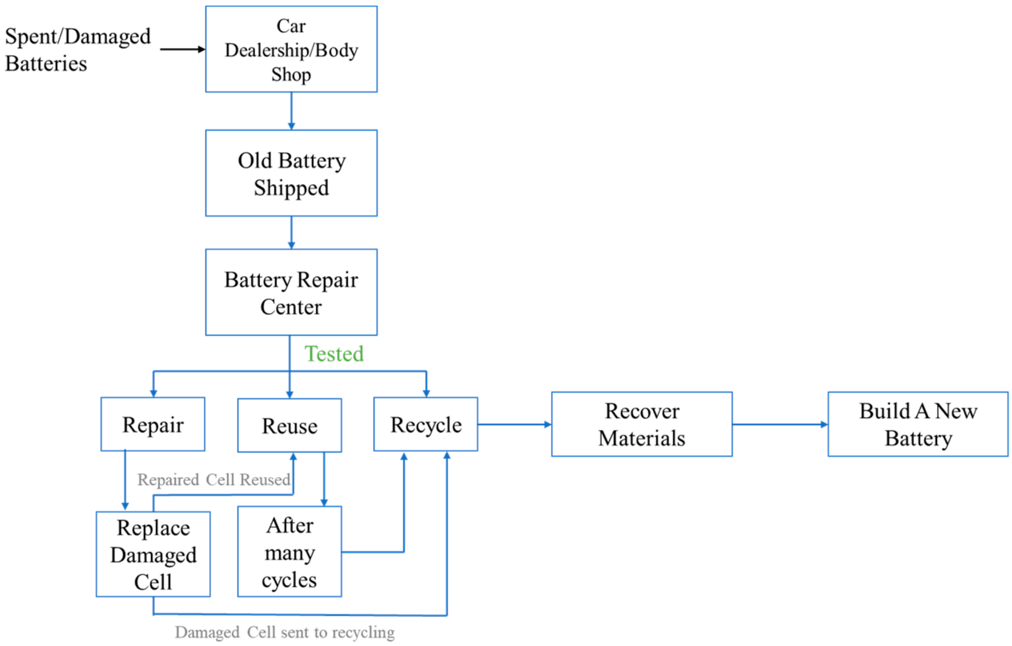

Figure 1. Life of LIBs from end-of-life through recycling.

The complexity of transporting these batteries is amplified by the diverse chemistries employed in the batteries of today's EV industry, such as Lithium Cobalt Oxide (LCO) and Lithium Manganese Oxide (LMO) [4], making the establishment of uniform safety guidelines a significant challenge. This study provides a detailed analysis of the logistical, environmental, and economic challenges and opportunities presented by crucial stages in the battery lifecycle. With an emphasis on recycling lithium-ion batteries (LIBs), their importance is explored in the context of the growing EV market, combined with concern for environmental protection and the challenges of safely transporting these potentially hazardous materials. An in-depth analysis of different recycling companies available in the U.S. and around the world contributes to a more comprehensive understanding and improvement of sustainable practices in battery management. This article was extracted from an internal report submitted to the New Jersey Department of Environmental protection to facilitate the effective management of EOL LIBs in EV.

2. Environmental Impacts of LIB Production

The production of lithium-ion batteries (LIBs) poses significant environmental challenges, mainly due to their chemical composition, material deterioration over time, and the energy-intensive manufacturing processes. As demonstrated by Väyrynen and Salminen [5], despite the technological advancements in lithium electrode materials that have significantly improved battery performance, the scaling up of production, coupled with strict safety requirements, especially for electric vehicle applications, is costly. The current cost for LIBs is a few hundred dollars per kWh. Life cycle assessments (LCA) have revealed that LIB production consumes approximately 50–65 kWh of electricity per kWh of battery capacity, excluding the mining and processing stages [6]. Furthermore, Gaines et al. [7] showed that nearly half of the battery-production cost arises during the assembly. Gaines et al. [7] also showed that a significant portion of the energy needed is associated with procuring high-demand materials such as aluminum and copper.

Addressing these environmental concerns, Chrodia et al. [8] and Romare [9] proposed that upscaling production and integrating renewable energy sources into the supply chain can considerably reduce greenhouse gas emissions and other toxic pollutants associated with LIB manufacturing. Chrodia et al. [8] demonstrated a potential reduction in emissions by nearly 45% in scenarios utilizing a cleaner energy mix, compared to traditional methods, which are reliant on fossil fuels. This shift not only emphasizes the role of renewable energy in reducing the environmental footprint of LIB production but also highlights the critical need for innovative recycling technologies that can further decrease the demand for raw materials by more than 50% [7]. Thus, while the demand for LIBs continues to grow, addressing the environmental impacts through cleaner energy sources and more efficient production processes remains necessary for sustainable development in this sector.

3. Battery Transportation

When consumers wish to dispose of spent LIBs, they typically visit a local battery repair or replacement shop. Although no specific federal law mandates these shops to accept all old LIBs, the U.S. Environmental Protection Agency (EPA) offers guidelines under the Resource Conservation and Recovery Act (RCRA) for handling and recycling these batteries [10]. It is important to note that many of these guidelines and rules cover all LIBs, not just those used in vehicles. Other state governments have also set specific regulations to facilitate this process for both non-EV and EV applications. In New Jersey for example, the current legislation mandates specific regulations requiring manufacturers to implement management plans for electric vehicle batteries, ensuring educational materials and cost coverage for end-of-life management [11]. These measures facilitate the proper disposal and recycling of LIBs, reassuring consumers about their batteries' responsible handling. After collection, the battery is sent to a designated recycling collection center.

From this collection point, the batteries are then transported to the nearest recycling facility. Throughout this transportation process, strict safety standards and protocols are followed to ensure secure handling. These include compliance with the UN 38.3 certification, which pertains to the safe transport of lithium batteries, and adherence to the U.S. Department of Transportation (DOT) packing requirements, which are also designed to minimize risks during transportation.

This comprehensive transport process ensures that spent LIBs are recycled in a safe and environmentally responsible manner, reflecting the growing emphasis on sustainable battery use and disposal practices.

3.1. Battery Certification

The United Nations has developed a certification system to enhance the safety of transporting hazardous materials, including EV batteries. These batteries must comply with certain standards outlined in the UN's Manual of Tests and Criteria [12].

Obtaining UN 38.3 Certification and following the required practices is essential for the safe transportation of batteries across different modes of transport. This certification is crucial not only to ensure safe transit but also to prevent potential penalties or customs delays. The UN system encompasses a comprehensive set of regulations and guidelines that dictate the safe handling and transportation of such materials.

3.2. UN 38.3 Certification

To ensure the safety of batteries for transportation, they must undergo a rigorous certification, involving eight distinct tests conducted by an accredited facility. These tests are designed to simulate various conditions the batteries might encounter during transit [13]:

1. Altitude simulation test: The experiment involves subjecting batteries to a sustained pressure of 11.6 kilopascals (kPa) for more than six hours. This pressure mimics the

environmental conditions at roughly 15,000 m altitude. Post-exposure, the batteries are inspected for any significant physical alterations such as leakage, rupture, or combustion. Additionally, the test includes a disassembly check and requires the battery to maintain a minimum of 90% of its original voltage after the test. This criterion ensures the battery's stability and functionality when subjected to low-pressure conditions, which it may encounter during high-altitude air transportation.

2. Vibration test: The battery is tested under vibrations typical of transportation to assess its durability and integrity. To pass, the battery must not exhibit any leakage, venting, rupture, disassembly, or fire. Additionally, it should maintain its voltage and other key performance criteria. This ensures that the battery remains stable and safe during transportation, including road, air, and sea travel.
3. Impact test: Applicable only to individual primary and secondary cells, this test involves subjecting the battery to an impact using a 9.1 kg weight, along with drop tests in its packaging. To pass this test, the battery must not show any signs of leakage, venting, rupture, disassembly, or fire. Additionally, it must not exhibit any significant degradation in performance, ensuring that it remains safe and functional despite the physical stresses it might encounter during transportation.
4. Thermal test: The battery undergoes temperature extremes, being kept at +72 °C for six hours followed by −40 °C for another six hours, repeated over ten cycles. Again, the battery must not show leakage, venting, rupture, disassembly, or fire. It should also maintain its voltage and other critical performance metrics. This test ensures the battery's stability and safety under extreme temperature variations that could occur during transportation.
5. Forced discharge test: This test evaluates the battery's performance under conditions of forced discharge, depleting its entire capacity. This test primarily looks for any abnormal responses, such as excessive heating, physical damage (including swelling or rupture), or leakage. The focus is not on the battery's recharge capability afterward, but rather on its ability to safely discharge without creating hazardous conditions. This test is crucial to ensure that the battery can withstand abnormal operating conditions without posing a safety risk.
6. Shock test: Here, the battery is tested for its ability to withstand heavy acceleration, simulating mechanical shocks. The specific rate of acceleration used is 34.6 g [14] (where "g" represents the acceleration due to gravity). This acceleration is applied in shock pulses in both positive and negative directions. The test simulates the type of mechanical shocks that a battery might encounter during transportation, ensuring that the battery can withstand such impacts without compromising its safety and functionality. After the test, the battery is examined to ensure there is no leakage, venting, rupture, disassembly, or fire. It is also important that the battery does not show significant degradation in its performance, such as a loss in voltage or capacity.
7. Overload test: The battery is charged with the recommended current 24 times for a duration of two hours each, and then monitored for a week for any signs of fire or disassembly. While the standard procedure does not explicitly state that the battery must be discharged between each charging cycle, in practice, the battery's usual discharge cycle might occur naturally due to its internal chemistry and design. To pass this test, there should be zero signs of fire, disassembly, leakage, or other safety hazards during the test period.
8. External short-circuit test: The test involves intentionally creating a short circuit between the battery's terminals to simulate a real-world short-circuit scenario. This is typically performed using a low-resistance conductor connecting the positive and negative terminals. To pass the test, the battery must not overheat dangerously, rupture, leak, or catch fire. The test is essential to ensure the battery's safety under conditions that could occur during use or transport, focusing on its physical integrity and thermal response under a forced short-circuit condition.

Successfully passing these tests is required for batteries to be certified as safe for transportation.

3.3. Packing Requirements

The Department of Transportation (DOT) in the United States has established comprehensive guidelines [15] for the packaging and transportation of lithium batteries. These regulations mandate clear labeling of lithium battery packaging, indicating the relevant UN identification number according to their size and type. The guidelines are categorized as follows:

- Guides 1 and 2 refer to UN ID UN3480, applicable to lithium-ion batteries. Guide 1 is for fully regulated cells and batteries (cells greater than 20 Wh and batteries greater than 100 Wh), while Guide 2 covers smaller cells and batteries (cells equal to or less than 20 Wh, batteries equal to or less than 100 Wh), and for highway and rail transportation only, cells not exceeding 60 Wh and batteries not exceeding 300 Wh.
- Guides 3 and 4 pertain to UN ID UN3481 for lithium-ion batteries packed with or contained in equipment. Guide 3 addresses fully regulated cells and batteries, while Guide 4 is for smaller cells and batteries, with similar capacity distinctions as Guides 1 and 2.
- Guides 5 and 6 relate to UN ID UN3090 for lithium metal batteries. Guide 5 is for fully regulated cells and batteries (cells greater than 1g and batteries greater than 2 g), whereas Guide 6 is for smaller cells and batteries (cells equal to or less than 1 g, batteries equal to or less than 2 g), and for highway and rail transportation only, cells not exceeding 5 g and batteries not exceeding 25 g.
- Guides 7 and 8 are associated with UN ID UN3091 for lithium metal batteries packed with or contained in equipment, with Guide 7 for fully regulated and Guide 8 for smaller cells and batteries, following the same size criteria as those in Guides 5 and 6.

Lithium batteries are classified under the miscellaneous hazard class 9. The DOT's guidelines ensure that lithium batteries are transported safely, depending on their size and whether they are packed, in compliance with the appropriate safety standards.

Determining the appropriate guide number for package labeling is crucial, based on the required specifications. These guidelines stipulate that the inner lining of the packing container should be a non-metallic material to prevent short circuits. The container must also protect the battery from contact with conductive materials and securely hold the battery in place.

3.4. Regulatory Framework for the Transportation and Recycling of LIBs

Transportation and recycling of LIBs are both governed by sets of stringent regulations aimed at ensuring environmental safety and reducing hazards. For transportation, in addition to the UN and US requirements described previously, packaging and shipping standards, particularly for hazardous materials such as lithium batteries, are dictated by both European and International regulations. These include the regulation concerning: International Carriage of Dangerous Goods by Rail (RID) for rail transport, the European Agreement concerning International Carriage of Dangerous Goods by Road (ADR) for road transport, the European Agreement concerning International Carriage of Dangerous Goods by Inland Waterways (ADN) for waterway transport, the International Maritime Dangerous Goods Code (IMDG) for maritime transport, and the International Air Transport Association Dangerous Goods Regulations (IATA DGR) for air transport [16–20]. These comprehensive regulations specify the requisite packaging, marking, and transportation methods, aiming to ensure the safe and secure transit of these materials and minimize risks. These standards extend the UN and US guidelines with mode-specific requirements. These include specialized packaging, additional documentation, and certain operational procedures to further minimize risks associated with the transport of LIBs.

In the realm of recycling, LIBs in the United States are subject to mandatory federal and state laws. The current guiding principle of these regulations is the "Battery Act", or the Mercury-Containing and Rechargeable Battery Management Act of 1996. This act was implemented to foster the recycling and responsible usage of batteries, including lithium-ion types, to prevent environmental damage through inappropriate disposal. Key provisions of the Act include the prohibition of the sale of batteries with certain mercury content, mandatory clear labeling on rechargeable batteries to encourage recycling, the establishment of convenient recycling programs by manufacturers and retailers, and the requirement for rechargeable batteries to be easily removable from consumer products. This legislation seeks to reduce the environmental impact of battery disposal, lessen the amount of hazardous waste in landfills, and facilitate the recovery and reuse of valuable materials found in batteries. The aim is to mandate environmentally conscious handling and recycling processes for these batteries, though specific requirements may vary across states [21].

3.5. Context and Prevention Measures for EV Battery Fire Incidents

The primary concern in transporting lithium batteries, especially regarding fire risks, stems from their tendency to ignite. When such fires occur, it has been found that allowing the battery to burn out is the most effective response. This is because LIBs, as recent experiences of firefighters have shown, can easily reignite. The self-oxidizing nature of the lithium salts within these batteries means they cannot be extinguished with conventional techniques, as they continue to burn without external oxygen [22]. Firefighters, therefore, focus on containing the fire to prevent it from spreading until it naturally dies out. Various factors, including design flaws, overheating, physical damage, improper charging, battery swelling, or internal damage, can cause these fires [23]. It is important to note that for small fires caused by LIBs, firefighters can typically use water to contain the fire [24], although some reports suggest that there is a possibility of reignition.

However, electric vehicle (EV) batteries are less prone to fires than is often assumed. In reality, EV fires are relatively rare. In Sweden for example, between 2018 and 2022, the occurrence of fires in electric vehicles (EVs) and hybrids was notably low, with only 29 EVs and 52 hybrids reported to have caught fire. This contrasts sharply with the annual average of 3400 fires in gas- and diesel-powered vehicles, indicating that EVs constituted merely 0.4% and hybrids 1.5% of all passenger vehicle fires annually [25]. Comparatively, traditional vehicles accounted for 98.1% of such incidents. This is particularly significant considering the increasing prevalence of EVs and hybrids in Sweden. By 2021, EVs had reached a substantial market share of 32.2% of all new vehicle registrations, a significant rise from 2.5% in 2015. Furthermore, in 2022, the share of newly registered rechargeable passenger cars, including EVs and plug-in hybrids, climbed to 56% [26]. These figures underscore the rarity of battery-related fires in EVs and hybrids in Sweden, highlighting their relative safety compared to traditional vehicles. This and similar data are crucial in dispelling concerns about EV safety and promoting sounder environmental practices, such as battery recycling. Despite the low incidence of EV fires, they still pose risks, underscoring the need for cautious handling and recycling of EV batteries and emphasizing the importance of developing robust safety protocols in the recycling industry.

To mitigate the risk of EV battery fires, the US Fire Administration [27] advises several safety precautions, especially regarding EV charging. Key recommendations include adhering to the manufacturer's charging guidelines, using a certified charging device, and plugging Level I chargers directly into a suitable outlet, avoiding adapters or extension cords. Installing a residual current device to cut off power in case of faults, keeping charging components away from children, and maintaining them as per manufacturer's instructions are also crucial. Chargers showing signs of wear should be replaced, and it is important to ensure that charging station outlets are covered to prevent water ingress, and to follow manufacturer's guidelines for charging in wet conditions. These measures aim to significantly reduce the likelihood of fire incidents in EVs, thereby extending the lifetime of the battery, among other benefits.

3.6. Evaluating EV Battery Transport Safety Regulations

Transportation of LIBs carries inherent risks due to their hazardous nature and potential for environmental impact. A recent example of these risks materialized on 28 December 2023, with an incident involving the cargo ship Genius Star XI. The ship, laden with a substantial quantity of LIBs, suffered a fire in its cargo hold while traveling from Vietnam to California. The U.S. Coast Guard was alerted to this emergency, and the fire was effectively controlled [28]. Another significant event occurred on 13 November 2022, aboard the oil tanker S-Trust in Baton Rouge, Louisiana. Here, a fire was triggered by a thermal runaway in a lithium-ion battery cell from a handheld radio, leading to extensive damage, estimated at $3 million, but no human injuries [29]. These incidents underscore the critical need for stringent safety protocols in the transportation of LIBs. Adherence to the guidelines set by the Department of Transportation (DOT) and other U.S. agencies is vital for mitigating risks. While these occurrences resulted in material damage, the absence of human casualties highlights the effectiveness of current safety measures in handling and transporting these hazardous materials.

Moreover, there is an increasing emphasis by state governments on enhancing their autonomy in EV battery recycling. For example, as mentioned earlier, the current legislation in the State of New Jersey fosters a local ecosystem for recycling these batteries. The New Jersey "Electric and Hybrid Vehicle Battery Management Act" mandates that electric vehicle battery manufacturers formulate strategies for the safe reuse, recycling, or proper disposal of LIBs from electric and hybrid vehicles. This law enables consumers to deliver their EV or LIBs either to a location designated by the manufacturer or to a recycling center authorized by the NJ Department of Environmental Protection. Moreover, it seeks to prohibit the landfilling of these batteries, aligning with the objective of establishing a circular economy in battery recycling [30]. Similarly, in Washington State, the legislature passed a law in 2023 to establish a product stewardship program for batteries, requiring battery producers to create a statewide collection system for portable used batteries by 1 January 2027. This initiative aims to enhance the recycling process for batteries, including those used in electric vehicles [31]. Analogously, California has been actively developing a policy for EV battery recycling, inspired by Assembly Bill 2832. This bill led to the formation of an expert group to recommend policies for increasing EV battery recycling. The proposed policies could potentially lead to a comprehensive LIB recycling regulation in the U.S., emphasizing producer responsibility and other key areas, such as access to battery information, industry support, and logistics safety [32]. These state-level efforts reflect a growing commitment to sustainable battery use and recycling, in response to increasing electric vehicle adoption.

As an example of current availability of battery collection facilities, the nearest such location for spent EV batteries in New Jersey at this time is Greentec Auto in Livingston, NJ. This center focuses on replacing hybrid battery packs and provides mobile installation services across the New York metropolitan area, encompassing New Jersey and nearby regions [33]. This situation is likely to evolve, with an anticipated increase in battery recycling and repair centers throughout the New Jersey area, reflecting a broader national trend towards a circular economy for battery component materials. This pattern of change gained momentum with the 2022 Inflation Reduction Act. The establishment of additional recycling facilities, particularly in areas with higher populations, aims to shorten transportation distances. However, the primary goal is not safety concerns but rather enhancing the recycling market's efficiency and making battery disposal more convenient for residents, as well as for those responsible for the collection and processing of spent batteries. With the growing prevalence of electric vehicles (EVs) and the U.S. government's recognition of this trend, expanding recycling infrastructure and capacity is viewed as essential to meet the rising demand for such services [34]. This expansion is a strategic step towards achieving a fully circular economy in EV battery production, focusing on increased efficiency and sustainable practices.

3.7. Collection and Testing of LIBs in the USA

In the United States, there exists a comprehensive network specifically designed for the transportation and collection of LIBs across various applications, not limited to those used in electric vehicles (EVs). This network includes key shipping carriers, such as CEVA Logistics, UPS (United Parcel Service), FedEx, DHL, AIR 7 SEAS Transport Logistics Inc. (Oak Creek, WI, USA), USPS (United States Postal Service), CHEMTREC, Crane Worldwide Logistics, Team Global, LR International, and ZARGES. These organizations provide specialized services to ensure the safe and compliant transport of LIBs, encompassing a wide range of uses beyond just EVs, such as consumer electronics, industrial applications, and portable devices [35]. It is fair to say that due to the size of the batteries used in EVs, much of the existing LIB transportation infrastructure, being designed for smaller batteries, is not capable of effectively transporting EV batteries. Specially created systems have been put together, still following the existing regulations and requirements for safe transportation.

Complementing this transportation network for smaller batteries, there are dedicated battery centers, notably the ReCell Center and the Global Battery Alliance. The ReCell Center plays a pivotal role in the collection of LIBs. With multiple drop-in locations available, it provides a convenient way for individuals to dispose of their batteries responsibly. Once collected, these batteries are then sent to specialized recycling companies [36]. Similar to the ReCell Center, the Global Battery Alliance offers a network of drop-in locations for the collection of LIBs. These batteries are then forwarded to recycling companies for processing. The Alliance operates in various locations, including Michigan and New Jersey, making it accessible to a wide audience [37].

3.8. Challenges and Future Outlook of Battery Transportation

The logistical challenges of transporting end-of-life (EoL) lithium-ion batteries (LIBs) from electric vehicles (EVs) are significant, presenting both environmental and economic burdens. The process of collecting, dismantling, and recycling these batteries is essential for diverting them from waste streams, yet it requires careful consideration of the impacts associated with these activities. Hendrickson et al. [38] emphasize that the specific location of recycling facilities and the choice of transportation mode have a profound effect on the overall human health impacts and the economic costs involved. Additionally, the transportation of EoL batteries contributes between 1–3.5% of life-cycle greenhouse gas (GHG) emissions for a recycled battery, highlighting its importance in the recycling supply chain [39].

The cost implications are closely tied to the logistics of battery recycling. The relationship between transportation costs, the number of dismantling facilities, and the overall environmental and economic impact is complex. With an optimal recycling facility size identified at 7000 tons/year, the marginal costs, including capital and transportation costs, were found to be significantly affected by the mode of transportation, with rail transport reducing both economic costs and GHG emissions considerably [38]. This finding points to the necessity of optimizing the recycling infrastructure to balance between minimizing transportation costs and reducing the number of facilities to lower capital investments.

The proposed solutions to address these challenges include the adoption of multimodal transportation strategies and the consideration of a decentralized recycling approach, which would necessitate several smaller facilities strategically located to optimize logistics [38]. Such strategies not only have the potential to reduce the environmental and economic burdens associated with the recycling of LIBs but also offer an opportunity for batteries to be utilized for second-life applications before recycling, thus further offsetting fossil fuel use. Future research directions suggest a focus on regionally optimized system design, which would identify preferable sites for new facilities, considering cost, GHG emissions, and local environmental and social impacts, ultimately reflecting the current state of the industry and improving the economics of recycling [39].

4. EV Vehicle LIB Repair

In the realm of EV battery management, the focus is primarily on two critical aspects: extending battery life and promoting sustainable practices. At the forefront of life-extension are repair centers, where teams of certified high-voltage experts work on LIB, aiming to reduce waste by repairing batteries to facilitate continued or repurposed use. This approach is both cost-effective and environmentally friendly. The process begins with the repair centers attempting to fix a failed battery, ensuring it can be reused in the vehicle, thus eliminating the need for a replacement. This is the most sustainable and economical method of handling failed batteries. If the battery is beyond repair for vehicular use, it is either repurposed for non-automotive applications, such as energy storage, or sent for recycling to reclaim the valuable raw materials for new EV battery production [40].

The repair procedure involves testing and diagnosing the battery, followed by either repairing it or replacing certain components. This is crucial for extending the lifespan of EV batteries, which can contain hundreds to thousands of cells. By replacing only the faulty parts, such as a single module or a malfunctioning battery management system, the need for entirely new batteries is reduced, thus conserving resources and reducing carbon emissions. Despite the advantages, EV battery repair is fraught with challenges. Repairing LIB batteries is complex due to their design and construction. Many batteries, particularly in e-bikes and EVs, are encased in heavy-duty materials and contain cells that are glued or welded together, making individual replacement difficult. Additionally, manufacturer restrictions and software that shuts down the battery if unauthorized tampering is detected further complicate the repair process. Although manufacturers claim that these designs ensure safety and performance, they hinder repairability, so this may be an area that merits future change. The dangers of battery repair, such as the risk of fire, explosion, or electric shock, also mean that it is a task strictly for trained professionals. The current scarcity of skilled repair personnel, combined with the design challenges, limit the feasibility of LIB battery repair at present. In addition, to reduce fire hazardous, fire retardants are added to LIB batteries, making them almost impossible to repair. While there are regulations for e-bike batteries, such as those recently announced by the federal Consumer Product Safety Commission and the New York City Council, regulations for EV battery repair are still minimal or lacking. This gap in rulemaking and the varying design approaches by manufacturers, from serviceable to non-serviceable batteries, pose significant challenges in the pursuit of sustainable and economical battery management [41].

Technologies, Incentives, and Frameworks Surrounding Repair Initiatives

The regulatory framework surrounding the repair of lithium-ion batteries (LIBs) for electric vehicles (EVs) is evolving to support incentives for LIB repair and reuse, as highlighted by the US Environmental Protection Agency (USEPA). The USEPA clarifies that activities related to the repair, reuse, or repurposing of electronic devices, including LIBs, are not considered waste management and are exempt from certain regulatory requirements, encouraging the development of repair technologies and methodologies [42]. This regulatory stance opens the door for innovative repair technologies to flourish, particularly those that offer environmental and economic benefits.

Current repair technologies face challenges, particularly in the direct repair of spent cathode materials, where traditional methods such as pyrolysis and hydrometallurgical leaching aim to extract valuable metals but may result in potential secondary pollution [43,44]. Innovations in direct repair technologies, such as solid-phase sintering, show promise for their low cost and high value-added advantages, offering a more sustainable alternative by reducing recycling costs and environmental pollution [45,46].

The solid-phase sintering method has demonstrated success in repairing failed $LiCoO_2$ cathodes, resulting in lower electrochemical impedance and faster Li+ diffusion compared to the original materials. This method not only improves the structural and electrochemical performance of repaired cathode materials but also offers higher environmental and economic benefits compared to conventional recycling techniques, indicating a greater potential for commercialization [45].

On the other hand, strategies for extending the usage of battery systems, such as cell replacement, face economic and logistical challenges. Traditional pack maintenance approaches, which involve replacing all cells to prevent mismatches, are not economically viable for large battery packs. An alternative strategy involves maintaining an inventory of cells aged to different levels and selecting appropriately aged cells for repair, thereby minimizing imbalance and premature aging. This approach, coupled with the potential for repurposing used cells in less demanding applications, offers a promising path for enhancing the effective cost and environmental sustainability of battery systems [47].

5. Battery Testing

Electric vehicle (EV) battery testing encompasses a range of methodologies to ensure the health, safety, and performance of these critical components, both when they are new and throughout their service life.

For new batteries, testing includes capacity testing, which measures the actual storage capacity against the rated capacity through a complete charge–discharge cycle. Cycle life testing evaluates endurance over numerous charge–discharge cycles, determining when capacity falls below 80% of the original capacity. Rate performance testing assesses efficiency under different charging and discharging rates, while thermal testing examines behavior under diverse temperature conditions. Vibration and shock testing simulate physical stresses in vehicles, and environmental testing exposes batteries to conditions including humidity or corrosive atmospheres [48]. These procedures are guided by internationally recognized standards, such as ISO 12405 [49], SAE J2464 [50], and the IEC 62660 [51] series, focusing on performance, reliability, safety, and abuse testing for EV batteries.

In contrast, in-service testing of EV batteries, used in actual vehicles, involves regular monitoring and assessment to ensure ongoing safety and efficiency. This includes state-of-health (SoH) assessments, voltage and temperature monitoring, charge–discharge cycle analysis, and the use of diagnostic software. Physical inspections are also vital for spotting potential issues, such as corrosion or damage. In-service testing aims to identify batteries that may need repair or maintenance, thereby extending their life and preventing premature disposal [52,53].

Together, these testing regimes for new and in-service batteries ensure that EV batteries meet essential criteria for reliability, safety, and efficiency throughout their lifecycle, which is critical for the performance and broader acceptance of electric vehicles.

5.1. Emerging LIB Testing Technologies

As part of the movement towards electrifying the U.S. transportation system, the United States Department of Energy (USDOE) set the ambitious goal of achieving safe and reliable charging of electric vehicles (EVs) to 80% state-of-charge (SOC) within 15 min. However, to reach this aim, understanding and mitigating the degradation mechanisms in LIBs under extreme fast charging (XFC) conditions is crucial. Current XFC technologies result in significant capacity loss, primarily due to irreversible lithium (Li) plating on the anode and detachment of cathode particles, highlighting the need for advanced testing technologies to characterize these degradation modes [54–56].

Emerging testing technologies focus on both local and global analysis methods to provide insights into the spatial heterogeneity of degradation and overall cell performance. Techniques such as optical imaging, scanning electron microscopy (SEM), and nuclear magnetic resonance (NMR) imaging offer local perspectives on degradation, enabling detailed understanding of where and why Li is lost within a cell. Global techniques such as differential voltage analysis (dV/dQ) and coulombic efficiency (CE) measurements offer overarching data on the cell's health and performance, aiding in the comprehensive assessment of battery degradation [57,58].

Looking forward, addressing the challenges posed by Li metal anodes, such as the formation of metallic Li dendrites and ensuring compatibility with solid-state electrolytes, is paramount for the next generation of LIBs. Innovations in current collector materials, host electrode architectures, and electrolyte compositions are crucial for improving Li reversibility and minimizing dendrite formation, thereby enhancing the safety and cycling behavior of solid-state Li-metal batteries (LMBs). These advancements, alongside tailored anode-electrolyte interfaces and novel detection techniques are essential for realizing XFC capabilities and advancing the commercial viability of all-solid-state batteries [59,60]. As the field progresses, the role of testing technologies in detecting irreversible Li loss and optimizing battery design for XFC will become increasingly significant, driving innovations that ensure the safety, efficiency, and longevity of next-generation EV LIBs.

5.2. Standard Harmonization Efforts for Testing LIBs

With novel technologies for LIBs being developed every day, testing standards are also trying to keep up with this evolving field to ensure that proper precautions are being implemented without impeding innovation. Specifically, the IEC 62133 standard, essential for ensuring the safety of portable secondary cells and batteries, has undergone significant revisions to address the evolving landscape of battery technology. Notably, the 2017 update split the standard into two parts: IEC 62133-1 [61], focusing on nickel-based batteries, and IEC 62133-2 [62], dedicated to lithium-based batteries. This division reflects the industry's shift towards lithium technologies, given their prominence in modern applications due to their higher energy density and efficiency.

The adoption of IEC 62133-2 by the IECEE for the Certification Body (CB) demonstrates its significance in harmonizing battery safety testing on a global scale. This harmonization supports international trade and compliance, setting a unified benchmark for the safety of lithium batteries worldwide. As technology progresses, updates to these standards are anticipated, reflecting new insights and industry practices to maintain and enhance safety protocols [63].

6. EV LIB Reuse

EOL LIBs still retain a significant recharge capacity, typically 70% to 80%, once they are removed from an EV [64]. Reusing EOL EV batteries in "second life" applications can help to extend the usable life of a battery before it is ultimately recycled.

6.1. Reuse in Electric Vehicles

Many auto-repair shops and auto mechanics sell EOL EV batteries to operators who create a revamped or rehabilitated battery from the packs and cells that have sufficient remaining capacity [64] through a process known as refurbishment. In these refurbished batteries, the good cells in EV batteries are recovered and used. The operators then resell this refurbished battery to consumers. Refurbished batteries are a promising approach to extending the lifetime of an EV battery, but combining cells of different age and capacity without a proper battery management system or proper ventilation can lead to overheating and could even cause fires [65]. Thus, a system must be developed to ensure that batteries that are placed in the same module are compatible with one another.

Tesla customers have the following three options for replacing failed EV battery packs [66]:

1. Customers can bring their car to a Tesla-authorized facility: Rather than replacing just one module, Tesla installs a completely new (will cost up to $25,000) or remanufactured (will cost between $13,000 and $17,000) battery pack and then sends the old one to their battery plants for repair, refurbishing or recycling. While this returns the vehicle to a near-new condition once serviced, this process is much more expensive than other alternatives.
2. Customers can visit third-party repair shops: This option is much more affordable and will only identify the specific modules that have failed. However, since these

shops are not authorized by Tesla, the customer must take precautions in choosing which shop to go to.
3. Customers can replace the battery at home: This option is the cheapest alternative but requires a considerable time commitment due to the steep learning process. In addition, customers could hurt themselves by working with the hazardous battery materials.

While the cost for the second and third option is not specified, as it is highly variable, it can be estimated using several assumptions. For the second option, which involves visiting third-party repair shops, the assumptions include lower labor costs than Tesla-authorized facilities and the replacement of specific battery modules rather than the entire pack. Under these assumptions, the cost could range between $5000 and $10,000, reflecting the savings from targeting specific failed modules and less expensive labor.

For the third option, replacing the battery at home, the assumptions include the availability of necessary tools, the purchase of second-hand parts or non-Tesla components, and no labor costs. The estimated cost in this scenario ranges from $2000 to $5000. This lower cost range considers the absence of professional labor charges and the potential use of more affordable parts, though it factors in expenses for tools and safety equipment.

These numbers are speculative and highly dependent on various factors, such as the specific Tesla model, the extent of repair needed, and local market conditions for parts and labor. The DIY approach, while cheaper, carries risks due to the technical complexity and safety concerns of working with EV batteries.

6.2. Reuse of Spent EV LIBs as Energy Storage Systems (ESSs)

Exhausted EV batteries could also be applied in home energy storage systems [67], or in some analogous commercial applications. However, according to Tesla's former Chief Technology Officer and founder of Redwood Materials, Mr. J.B. Straubel, one of the biggest barriers to reusing batteries in ESSs is the rapidly changing battery storage technologies. The technology found in these batteries will be a decade old by the time they make it to the second-use market. Thus, reused batteries likely may not be compatible with future storage systems.

No matter the application in which EV batteries are reused, the issue of liability is a large barrier facing reuse because repurposed batteries have a greater risk of failure. If the batteries fail in a way that causes harm to human health or the surrounding environment, it is difficult to trace back the battery to the original manufacturer with the current tracking system [64].

6.3. Battery Swapping

Battery swapping or battery-as-a-service allows EV owners to replace the discharged batteries with charged ones at the swap stations. When the battery is discharged, the owner can exchange it for a fully charged one. This will address the problem of setting up charging stations and also reduce range anxiety for drivers. Battery swapping allows better management and use of EV batteries. However, the ability to accomplish this easily would depend on the design of the vehicle. For some EVs, battery exchange would require major disassembly of the vehicle.

6.4. Potential and Challenges Faced by Reuse Technologies

The widespread adoption of lithium-ion battery (LIB) reuse practices presents a promising avenue to enhance the economic viability and environmental sustainability of electric vehicles (EVs). However, this potential is hindered by several technological challenges and regulatory barriers. In order for the transition of LIB packs from EVs to energy storage systems to be successful, major challenges need to be addressed, such as significant differences in operational conditions, including charge and discharge rates and environmental stressors. To ensure safety and performance, retired battery packs must obtain new certifications, which necessitates the development of new standards for pack classification, cell grading, pack recombination, and comprehensive inspection and verification procedures. Additionally, designing energy, thermal, and safety management systems specifically for second-use applications, accurately predicting the aging conditions and energy capacity of used batteries, and integrating recycling with environmental protection are crucial steps [68].

The economic aspects of battery reuse also pose significant considerations. The cost of LIB packs constitutes a substantial portion of the total EV cost. Extending the service lifetime of these packs through second-use applications in energy storage could substantially reduce the overall costs and promote EV market penetration. Nevertheless, efficiently achieving pack classification, cell grading, and recombination, alongside precise evaluation of battery packaging and performance prediction for second-use applications, remains a challenge. This is further complicated by the need to develop real-time state-of-health (SOH) monitoring and advanced battery management systems (BMS) to safeguard against potential overuse or failure of re-manufactured packs [69].

Lih et al. [70] conducted an economic analysis that illustrated how strategic recycling and re-manufacturing technologies applied to retired LIB packs could achieve a net profit of close to 35% over 15 service years, with the potential for higher returns with the extension of the second-use life of the battery. This underscores the importance of overcoming the aforementioned challenges to unlock the significant economic and environmental benefits of LIB reuse. The successful implementation of these practices depends on technological innovations, cost-effective solutions, and the establishment of supportive regulatory frameworks to navigate the complex landscape of battery reuse in the transition towards sustainable mobility [70].

7. Recycling of EV Lithium-Ion Batteries

Recycling electric vehicle (EV) batteries offers significant benefits, both environmentally and economically. LIBs, the immediate power source for EVs, boast characteristics such as high discharge power, absence of memory effect, high energy density, and a lifespan of 10–20 years. Given that the availability of key elements, such as lithium, cobalt, and nickel, is naturally limited, and their demand is set to surge with increasing EV production, recycling emerges as a crucial strategy to maintain availability and price stability. This approach not only extends the use of these finite resources but also aligns with the growing demand, as depicted in Figure 2.

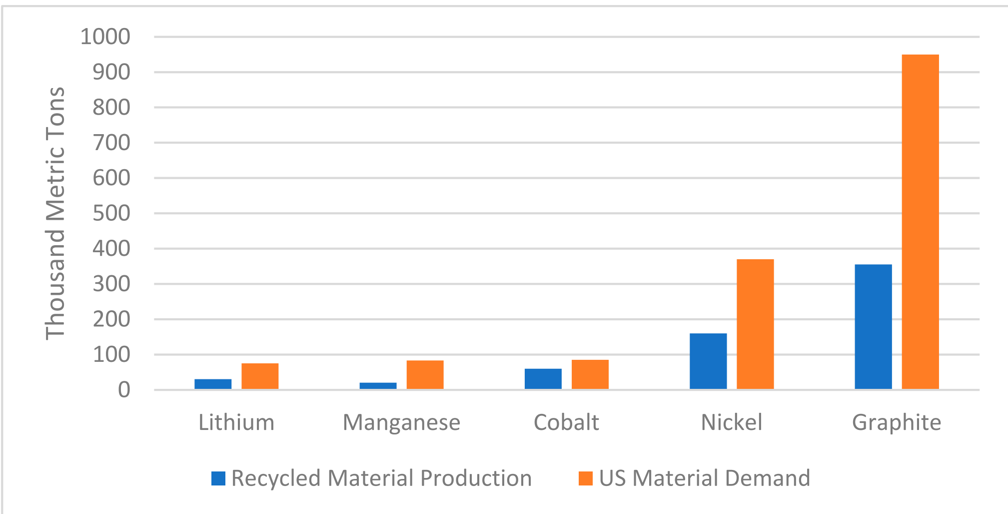

Figure 2. Material demand in the USA vs. recycled material production.

The global demand for EV battery capacity, measured in gigawatt-hours (GWh), was around 120 GWh in 2019 and is projected to increase significantly to about 680 GWh by 2025 and 1525 GWh by 2030. This increase reflects the growing market for electric vehicles (EVs) and the corresponding need for more LIBs, as they are the primary technology used in EVs. The rise in GWh indicates a larger quantity and potentially larger size of batteries required to meet the power and range needs of an expanding number of EVs. Additionally, China's position as the largest EV market underscores its significant contribution to this increasing demand, influenced by its market dynamics, manufacturing capabilities, and government policies promoting EV adoption (refer to Figure 3). Notably, even after reaching the end of their primary usage phase, EV batteries retain over two-thirds of their original storage capacity. This residual capacity allows for their refurbishment and reuse, either in new vehicles or for lower-power stationary applications [71].

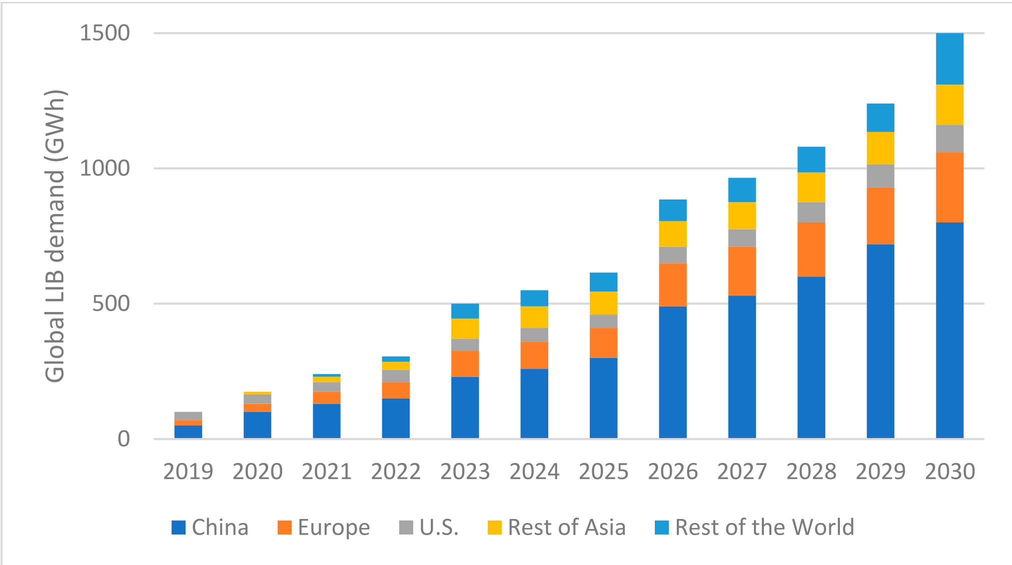

Figure 3. Projected global LIB demand across various industries.

Such recycling and repurposing can reduce the cost of new EVs, while potentially increasing the value of used ones, especially as the market for battery electric vehicles (BEVs) expands. This shift represents a significant opportunity to balance economic and environmental interests in the evolving landscape of electric-powered transportation.

Globally, there are fewer than a dozen major facilities dedicated to recycling electric vehicle (EV) batteries [71]. Together, these facilities have a material processing capacity of under 100,000 metric tons per year. In comparison, the amount of lithium recoverable through recycling EV batteries significantly surpasses that extracted from natural sources. This disparity underscores the importance of recycling in reducing the reliance on additional resource extraction for EV battery materials.

The substantial benefits of recycling LIBs are illustrated in Figure 4 [72]. This figure not only showcases the potential resource savings but also emphasizes the reduction in pollution. By decreasing the need for mining operations, recycling can markedly lessen the environmental impact. This highlights the urgent need to invest more in the development and expansion of EV battery recycling facilities, recognizing their role in both resource conservation and pollution reduction. Table 1 [73] compares natural resources consumed in new batteries versus those in spent batteries.

Besides the obvious economic advantages of recycling used LIBs, it is crucial to recognize the significant environmental consequences of improper disposal. Considering that the surge in electric vehicle (EV) purchases is largely driven by the desire to combat climate change, failing to recycle these batteries effectively would be contradictory to the very ethos behind acquiring EVs. There are several environmental and health-effect issues that could arise from the inadequate or inappropriate treatment of these batteries, including:

- Electric shocks from high voltage battery packs;

- Other additives in the batteries can form toxic and corrosive substances and may pose risks to human health as well as the environment;
- Fire accidents due to unsafe disposal of batteries;
- Soil and water pollution resulting from following the traditional method of burying batteries underground.

Compatison of different LIB Recycling Methods

Best ••••• •••• ••• •• • Worst

	Technology Readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Prodcution cost
Pyrometallurgy	•••••	•••••	•	•••	••	•	•	•••••
Hydrometallurgy	••••	•••	•••	••••	•••	•••	•••	•••
Direct Recycling	••	•	••	•••••	••••	•••	•••	•

	Presoting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	•••••	No	No	•••••	•••••	•••••	•••	No	•
Hydrometallurgy	••••	No	No	•••••	•••••	••••	•••	•••••	•••
Direct Recycling	•	•••••	••••	•••••	•••••	•••••	•••••	•••••	•••••

Figure 4. Comparison of different LIB recycling methods.

Table 1. Natural resources consumed in new batteries versus those in spent batteries.

	Natural Resources	Spent Batteries
One ton of battery-grade cobalt can come from:	300 Tons of Ore	5–15 Tons of Spent LIB
One ton of battery-grade lithium can come from:	250 Tons of Ore and 750 Tons of Brine	28 Tons of LIB

Given these factors, it is imperative to recycle spent LIBs. Recycling technologies have become highly effective, achieving up to 98% recovery of the materials essential for producing new batteries [74].

7.1. Driving Forces behind EV Battery Recycling

China's ascendance in electric vehicle (EV) battery production and recycling has prompted a competitive surge in the United States and Europe, highlighting the increasingly political nature of the recycling race. The EV battery market is dominated by China, accounting for around 80% of global LIB production in 2020 and selling nearly 6 million EVs in 2022. This lead is underpinned by a formidable manufacturing infrastructure, significant R&D investments, and competitive pricing, exemplified by the success of vehicles such as the MG4, which has dominated the UK market [75]. Moreover, China's prowess extends to the recycling of EV batteries. In 2022, China was responsible for nearly the entire global EV battery recycling activity, in a market that is anticipated to expand from $11 billion in 2022 to $18 billion by 2028, as per projections by EMR [76].

Wesselkamper et al. [77] forecast that China is poised to lead in EV battery recycling in the upcoming decades. Utilizing a dynamic material flow analysis, their research predicts that China will be self-sufficient in meeting its demand for lithium, a primary component for electric vehicle batteries derived from mining, starting from 2059. In contrast, similar self-sufficiency is expected to be achieved in Europe and the United States only after 2070. Regarding cobalt, the study anticipates that China's recycling capabilities will fulfill its needs by 2045, earlier than Europe's projection of 2052 and the U.S.'s estimation of 2056. For nickel, China is predicted to rely on recycling by 2046, again, preceding Europe and the U.S., which are projected to reach this stage by 2058 and 2064, respectively.

The profound impact of China's leadership is evident in the strategic responses of the USA and EU. The US Congress, for instance, included a clause in the Inflation Reduction Act that incentivizes the use of domestically recycled EV battery materials, catalyzing a shift towards local recycling efforts. Companies such as Ascend Elements and Altilium Metals are responding with significant investments in recycling plants, aiming to establish closed-loop supply chains and reduce dependence on Chinese and other imported resources. Despite these efforts, China continues to lead, with recent initiatives to set tougher standards and bolster research in recycling, countering the "anti-globalization" stance of the USA [78]. These geopolitical dynamic underscores the fact that the primary driver in the race for recycling supremacy is increasingly political, with the level of governmental support playing a crucial role in shaping the future of EV battery production and recycling.

7.2. Circular Economy of Recycling LIBs

The circular economy (CE) model is an innovative concept with the stated aim of maximizing resource efficiency and usage. It has gained popularity as a sustainable solution to address the environmental challenges presented by the production of LIBs especially for EVs. This model operates on three fundamental principles: eliminating waste and pollution, extending the use of products and materials, and saving natural ecosystems, thereby addressing the product lifecycle from material extraction to end-of-life management [79,80]. The CE not only seeks to transition material consumption towards a more sustainable, closed-loop system but also aims to support broader social and environmental objectives [81].

Globally, the recycling rate of LIBs remains very low, with less than 5% of LIBs being recycled, leading to significant environmental pollution and increased reliance on virgin raw materials [82,83]. To address these challenges, the CE model proposes two main strategies: recycling to recover valuable metals, such as lithium, cobalt, and manganese, and repurposing LIBs for second-life applications in stationary energy storage systems or other applications [84,85]. These strategies not only prevent harmful waste but also ensure the optimal utilization of valuable resources, highlighting the critical need for optimized recycling processes that minimize waste and are cost-effective. Furthermore, emerging recycling technologies seems to demonstrate promising advancements towards aligning with CE principles by recovering a broader range of components and reducing waste streams. However, these processes still face challenges, including losses of non-recovered materials and the need for further processing of recovered compounds to make them suitable for LIB manufacturing [86].

Despite the potential benefits, the adoption of CE for LIBs faces several challenges. These include the technical and economic barriers to achieving high recovery rates for critical materials such as lithium, which currently stands at 50–60% at the industrial scale, and the lack of comprehensive data on the reuse and remanufacturing of batteries, which are crucial for assessing their remaining life and suitability for second-life applications [87,88].

7.3. Recycling Methods for Spent EV LIBs

Over the years, a variety of battery recycling methods have been developed to enhance both the efficiency and return on investment of these processes. Key methods primarily encompass:

1. Pyrometallurgical recovery employs high temperatures (around 1500 degrees Celsius) to smelt and separate metallic alloys. Physical materials separation relies on properties such as particle size, density, ferromagnetism, and hydrophobicity, utilizing tools such as sieves, filters, magnets, and shaker tables to segregate materials, particularly separating electrode coatings and concentrating plastics.
2. Hydrometallurgical metals reclamation uses aqueous solutions to leach metals from cathode materials, producing pure material streams suitable for closed-loop battery systems.

3. Direct recycling involves removing and reconditioning cathode or anode materials from electrodes for reuse in remanufactured LIBs.
4. Biological metals reclamation leverages bacteria to digest and reduce metal oxides from cathodes, producing metal nanoparticles.
5. Froth flotation, a form of direct recycling, mixes metal oxide powders with a collector chemical, creating hydrophobic interactions with certain metals, separating them from hydrophilic substances.

Among these methods, pyrometallurgy, hydrometallurgy, and direct recycling are the most commonly used, with their benefits and drawbacks detailed in Figure 4 and discussed in subsequent sections.

7.4. Comparison of Different Recycling Methods

Each recycling method comes with its set of advantages and disadvantages. Pyrometallurgy (see Figure 5 offers a lower-cost alternative that is applicable to various battery types, including nickel-cadmium and lead-acid batteries. It boasts high metal recovery rates and eliminates sulfur oxide emissions. Despite these advantages, pyrometallurgy is capital-intensive, requiring significant investment and high-volume processing. It is also energy-intensive, necessitating expensive treatments of waste gases to prevent toxic air emissions, and results in the loss of some lithium and aluminum to slag [89].

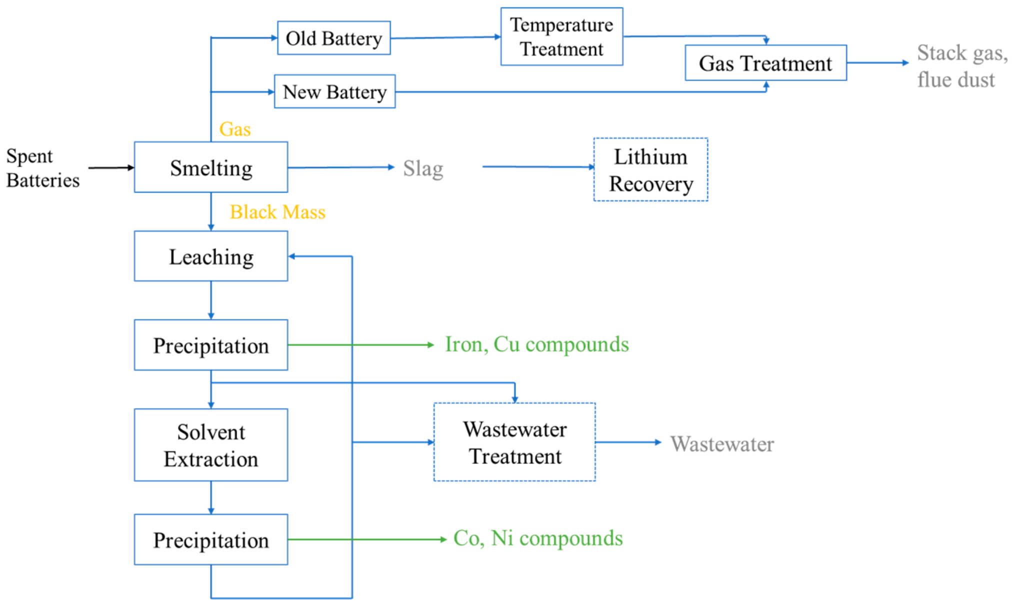

Figure 5. Flowchart of pyrometallurgical recycling process.

Hydrometallurgy (see Figure 6) stands out for its economic efficiency, requiring minimal investment and operating at low temperatures and energy levels. This method yields high recovery rates and is more energy-efficient compared to pyrometallurgy. It offers flexible separation and recovery processes, making it applicable to various battery chemistries and configurations. Despite these benefits, hydrometallurgy has environmental concerns, particularly the release of greenhouse gases. Anode materials are not recovered in this process, and solvent extraction is needed to separate cobalt and nickel. Furthermore, the process involves breaking down the cathode structure, size reduction, and dealing with high volumes of effluents that require careful treatment and disposal [89].

Froth flotation (see Figure 7) emerges as a highly efficient method, with enhanced recovery rates and adaptability to different electrode sizes. It is environmentally friendly, marked by minimal exhaust emissions and a low CO_2 footprint, and employs low or non-toxic solvents, leading to reduced energy consumption [90]. However, it does come with challenges, such as safety concerns due to the exposure of metals during the separation of components, which could lead to atmospheric pollution. Additionally, this method is limited to processing single cathode types, and mixing cathode materials may diminish the value of the recycled product [36]. The advantages and disadvantages of each method are summarized in Table 2.

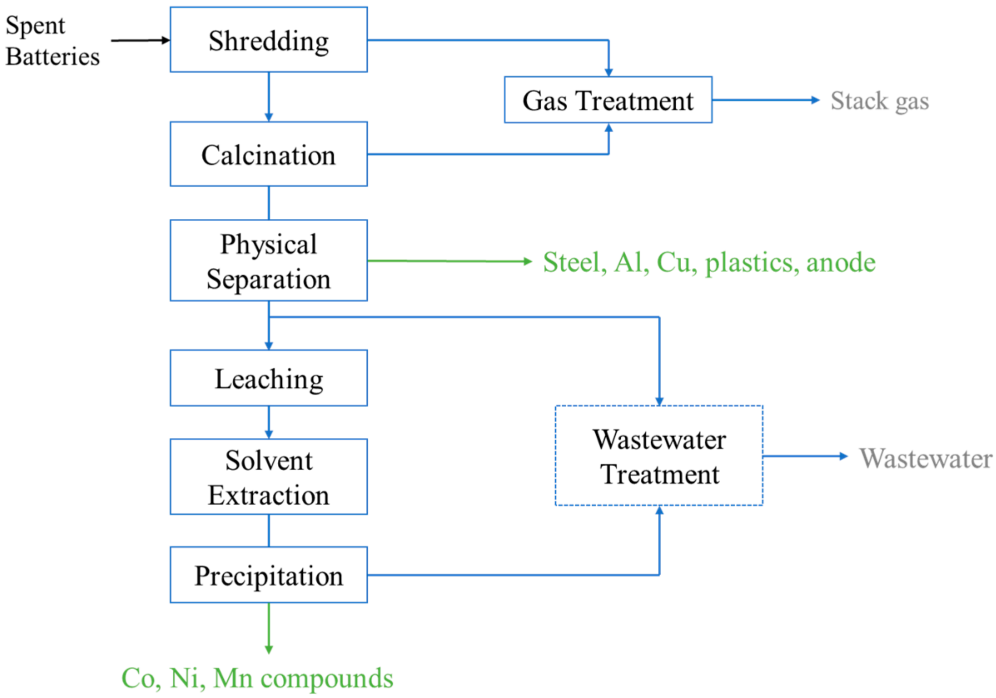

Figure 6. Hydrometallurgical recycling process.

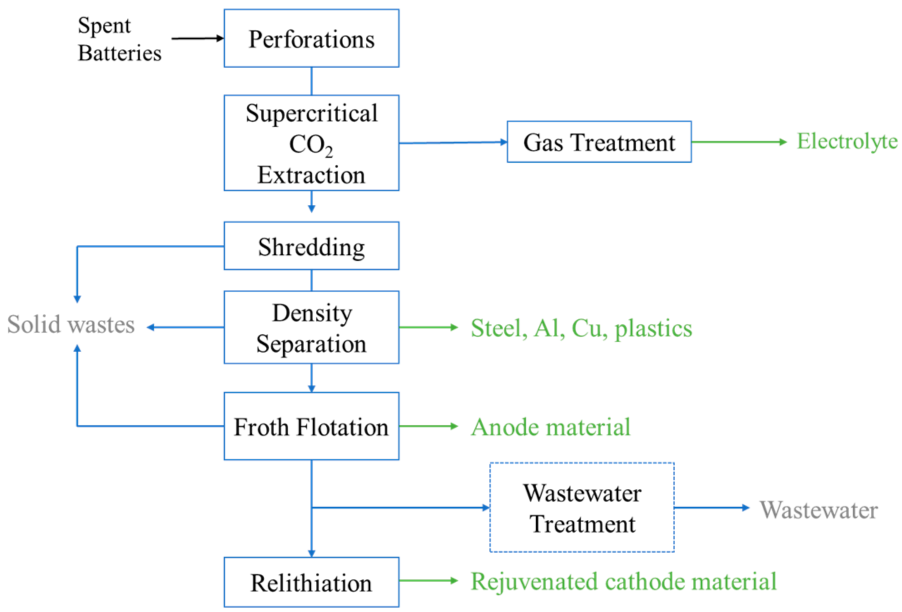

Figure 7. Froth flotation recycling process.

The recycling of LIBs commences with the collection and transportation of used batteries, adhering to strict regulations for handling hazardous materials. This aspect will be elaborated on in the following section. Upon reaching the recycling facility, the batteries are sorted based on the particular battery chemistry they represent or processed collectively, depending on the facility's method. A critical step before processing is the safe discharge of the batteries to eliminate fire or explosion risks, typically achieved through controlled draining of the remaining charge. Following this, the batteries undergo mechanical processes such as shredding, tailored to the battery size [73]. Shredding results in various outputs, including black mass (a mixture of anodes and cathodes), copper and aluminum foils, separators (plastic films), other plastics, steel canisters, and electrolytes [91]. Although thorough, this separation requires further processing for material isolation.

Table 2. Advantages and disadvantages of different recycling techniques.

Process	Advantages	Disadvantages
Pyrometallurgy [89]	1. Easiness of procedure 2. No necessity for passivation steps 3. Optimal technology readiness	1. High energy consumption 2. Hazardous gaseous emissions 3. Material loss (Li in the slag) 4. Need of Co LIBs chemistries (pre-sorting) 5. High capital costs
Hydrometallurgy [89]	1. High recovery efficiency 2. High quality outputs 3. Good technology readiness 4. Moderate energy consumption 5. No gaseous emissions 6. Recovery of all LIBs cathodic metals 7. Mild reaction conditions	1. Wastewater productions 2. Incomplete binder/electrolyte recycling 3. Complexity of procedure 4. Need of pre-treatments 5. Selectivity of reagents
Froth Flotation [66,92,93]	1. Flotation chemicals have negligible impact on the electrochemical performance of recycled active materials and are better for the environment 2. High purity levels 3. Less energy-intensive and does not require expensive equipment	1. Still needs to be implemented on a broader scale 2. Depends on rate of EV retirement. 3. Liability concerns 4. Heterogeneity in terms of battery models, forms, control, chemistry, and electrical characteristics can cause fires

A notable approach in recycling involves combining pyrometallurgical and hydrometallurgical processes. Initially, shredded battery components undergo pyrometallurgy, involving high-temperature processing in furnaces to create 'black mass', rich in valuable metals like lithium, cobalt, nickel, and manganese. This black mass is then treated through hydrometallurgy, using acid solutions for leaching out metals. The solution undergoes treatment to precipitate and purify each metal type [94]. This method, eliminating the need for initial sorting by battery chemistry type, has been effectively utilized by companies such as Redwood Materials, boasting a 95–99% recycling efficiency [95].

Additionally, alternative methods, including froth flotation, are employed for direct recycling, separating hydrophobic from hydrophilic materials without breaking them down to their raw forms [96]. Finally, the recycled metals are either sold separately or reintegrated into the manufacturing supply chain, where they can be used to produce new LIBs or other products.

Furthermore, when recycling batteries, it is important to consider the presence of PFAS used as fire retardants in older batteries [97]. Without proper recycling methods, PFAS can re-enter air and water streams. This issue is compounded by the large-scale recycling of batteries, which makes it challenging to separate older batteries containing PFAS from newer ones. Additionally, inadequate battery tracking systems can lead to environmental hazards, as even small concentrations of PFAS can be highly dangerous. Therefore, careful handling and monitoring are essential in the recycling process to prevent environmental contamination.

7.5. Mass Balance during Recycling

It is important to quantify the supply of spent LIBs and subsequently the amount of recovered material that can be produced using the recycling techniques discussed. Only hydrometallurgy and pyrometallurgy will be considered here, as they represent the two techniques that are adopted widely on an industrial scale [92]. While the exact number of spent LIBs available for recycling (input) and recovered materials (output) is unknown, this value can be approximated using the following assumptions:

1. Efficiency of hydrometallurgy is approximated at 95% for nickel, cobalt, and copper [98].
2. Overall efficiency of pyrometallurgy is lower due to material loss and is estimated at 90% [98].
3. The average weight of a car battery pack is around 500 kg, with varying content of nickel, cobalt, lithium, etc.
4. The assumed content of recoverable metals in a battery (nickel, cobalt, and lithium) is approximately 30% of the battery's weight.

Based on these assumptions, for every 1000 tons of batteries recycled:

- Hydrometallurgy: 1000 tons × 30% metal content × 95% recovery rate = 285 tons of metals recovered.
- Pyrometallurgy: 1000 tons × 30% metal content × 90% recovery rate = 270 tons of metals recovered.

Moreover, a study published by McKinsey in 2023 estimated that the global supply of RV batteries available for recycling would reach 900 kilotons in 2025 [99]. Assuming an equal division between the usage of hydro- and pyrometallurgy among recyclers:

- Total material recovery: 450 × 285 + 450 × 270 = 249,750 tons or 245.75 kilotons.
- Efficiency: $\frac{245.75}{900} \times 100 = 27.3\%$.

Hence, in 2025, recycling firms are expected to recover around 245.75 kilotons of precious metals from a total of 900 kilotons of spent LIBs, lending their operations a 27.3% efficiency.

7.6. Key Metrics in EV Battery Recycling

The escalating competition in EV battery recycling, spurred by China's dominance, has led US and European lawmakers to intensify efforts to strengthen local production capabilities and capacities. This strategic shift underlines a key concept: "Losing Nothing", which is crucial for maximizing US independence in the sector. With over 80 companies globally engaged in EV battery recycling and startups attracting significant investment, the industry is poised for exponential growth. By 2030, the volume of recyclable EV batteries is expected to surge by more than tenfold. The critical metrics in this arena include cost-effectiveness, life-cycle impact minimization, and return on investment for recycling processes. The race now focuses on extracting maximum value from recycled materials, particularly the "black mass" from EV batteries. Companies such as Ecobat are advancing recovery processes to achieve up to 90–100% yields, a significant factor as the EU mandates minimum recycled material content in EV batteries. Additionally, there is an industry focus on tracking old EVs for recycling, recognizing the high value of lithium, cobalt, and nickel in these batteries. Emphasizing this approach, BMW's sustainability chief Thomas Becker's statement to Reuters, "We've got to make sure we lose nothing", encapsulates the imperative of fully harnessing and recycling these valuable resources to reduce dependency and strengthen local industries [78].

Therefore, the ultimate goal in the evolving landscape of battery recycling is to achieve a scenario where new batteries are produced entirely from recycled materials. With China on track to be the first to attain this objective, U.S. and European legislators are urgently working to bridge the gap. This ambition aligns with the concept of a closed-loop system or circular-market, where materials are continually reused without waste, emphasizing the importance of enhancing recycling efficiencies. In the U.S., financial considerations such as cost and profit are less of a driver for recycling firms, as the focus shifts towards technological optimization to rival China's efficiency. This is exemplified by Redwood Materials, led by CEO J. B. Straubel. The company, bolstered by a $2 billion U.S. government loan, is expanding a battery material recycling and remanufacturing complex in Nevada. Straubel highlights the Inflation Reduction Act's perspective on recycled battery materials, considering them as "urban mined" resources, recovered from scrap instead of traditional mining, underscoring a strategic shift towards sustainable and efficient recycling practices in industries [78].

8. Recycling Companies

Globally, several prominent companies are recognized for their extensive capabilities in LIB recycling across a wide range of applications, not limited to electric vehicles (EVs). These companies include ACCUREC-Recycling GmbH (Krefeld, Germany), American Manganese Inc. (Surrey, BC, Canada), Battery Solutions(Wixom, MI, USA), Cirba Solutions (Charlotte, NC, USA), TES-Amm (Singapore, Singapore), SITRASA (Guanajuato, Mexico), and Li-Cycle Corp.(Toronto, ON, Canada) Table 3 provides details.

Table 3. List of large LIB recycling companies around the world.

Companies	Established	Headquarters	Information	Website
UMICORE N.V.	1989	Brussels, Belgium	UMICORE specializes in recycling, emission control catalysts, and rechargeable battery materials, among other clean technologies. The company is known as a leading recycler of precious metals.	http://umicore.com (accessed on 20 April 2024)
ACCUREC-Recycling GmbH	1995	Krefeld, Germany	A specialized company using advanced technologies and processes to recycle metal-electronic waste and value natural resources.	http://accurec.de (accessed on 20 April 2024)
American Manganese Inc.	1987	Surrey, BC, Canada	Company focuses on development of advanced battery technologies for recycling like creating sustainable solutions for recycling LIB.	https://recyclico.com (accessed on 20 April 2024)
Ganfeng Lithium Group Co.	2000	Xinyu, China	Ganfeng Lithium is one of the world's largest lithium compounds producers and is involved in lithium recycling as part of its integrated lithium resource operation.	https://www.ganfenglithium.com/ (accessed on 20 April 2024)
TES-Amm	2007	Singapore, Singapore	It provides a special series on safe and environmentally friendly recycling of LIB. Materials can be reused in production of new batteries making sure the proper handling and recycling of EV batteries.	http://www.tes-amm.com (accessed on 20 April 2024)
SITRASA	2003	Guanajuato, Mexico	It specializes in the treatment and efficient recycling of EV batteries.	https://www.sitrasa.com/en/quienes-somos-english (accessed on 20 April 2024)

Table 3. *Cont.*

Companies	Established	Headquarters	Information	Website
Li-Cycle Corp.	2016	Toronto, ON, Canada	It uses mechanical and hydrometallurgical processes to recover metals like lithium, nickel etc. and aims to reduce waste and greenhouse gas emissions.	http://www.li-cycle.com (accessed on 20 April 2024)
Redwood Materials	2017	Carson City, NV, USA	It uses mechanical, pyrometallurgy, and hydrometallurgical processes to recover metals like lithium, nickel, cobalt, and copper etc.	http://www.redwoodmaterials.com (accessed on 20 April 2024)
LG Energy Solution Ltd.	2020	Seoul, Republic of Korea	LG Energy Solution is focused on advanced lithium-ion batteries for electric vehicles and energy storage systems, with recycling initiatives as part of their sustainability commitment.	https://www.lgensol.com/ (accessed on 20 April 2024)
Hydrovolt	2020	Fredrikstad, Norway	A joint venture by Hydro and Northvolt, Hydrovolt is Norway's first large-scale lithium-ion battery recycler, utilizing renewable energy and aiming for high levels of metal recovery.	https://www.hydrovolt.com/en (accessed on 20 April 2024)

8.1. Car Manufacturers with Recycling Programs

Numerous automobile manufacturers have also ventured into the recycling of LIBs. They have been instrumental in developing innovative methods to repurpose these batteries beyond their initial use in electric vehicles (EVs). Prominent examples include the following:

Volvo: In collaboration with Battery Loop, Volvo is focused on developing batteries for EVs that can double as solar energy storage systems. These systems are designed to power car and bike charging points, demonstrating a commitment to sustainable energy solutions.

Tesla: The company has pioneered the establishment of Power Halls, facilities where they repurpose used batteries for energy storage. This initiative reflects Tesla's ongoing efforts to enhance energy sustainability.

Nissan: Nissan has introduced xStorage, a system that supports energy storage by reusing batteries. This approach contributes to the efficient utilization of battery resources and energy conservation.

BMW: Working with off-grid energy, BMW is committed to providing sustainable second-life solutions for batteries that have reached the end of their lifecycle. This collaboration is focused on ensuring these batteries continue to serve a purpose in an environmentally friendly manner.

Renault: In 2020, Renault launched the "Smarthub" project, which is geared towards supplying energy for various needs, including social housing, transport, and residential homes, capable of powering up to 1700 homes daily.

8.2. Major Recycling Companies in the US

Table 4 shows a list of U.S.-based companies specializing in the recycling of LIBs. It also shows the current LIB recycling capacity that should be substantially enhanced to accommodate the EOL LIBs of EVs currently used. Notably, Redwood Materials stands out in this landscape, demonstrating the highest current annual processing capacity among the recyclers examined in this article.

Table 4. Comparison of LIB recyclers.

Company	Founded	Location	Recycling Process	Key Partnerships	Annual Processing Capacity (Approx.)	Future Goals
Redwood Materials	2017	Carson City, NV, USA	Pyro- and Hydro metallurgy	Volkswagen, Panasonic, Volvo, Lyft, Proterra, Toyota, ERI, Ford	500,000 metric tons *	500 GWh by 2030
American Battery Technology Co. (ABTC)	2011	Reno, NV, USA	Hydrometallurgical	University of Nevada Reno, National Center for Applied Research	20,000 metric tons	Expand processing capacity
Cirba Solutions	1991	Charlotte, NC, USA	Cryogenic Method ^	KULR Technology Group Inc., Jacobs Group Inc., Honda	0.0125 tons *	Enhance safety measures
Ecobat	1994	Dallas, TX, USA	Hydrometallurgy	Tevva	10,000 tons	Exceed current recycling volume
Princeton NuEnergy	2019	Bordentown, NJ, USA	Low-Temperature Plasma-Assisted Separation ^^	A combination of Organizations ** including NJIT ***	500 tons	Secure safe harbor provisions
Li-Cycle	2016	Rochester, NY, USA	Hydrometallurgical	Veolia	75,000 tons	Scale up operations to 81,000 tons
Kinsbursky Brothers Intl.	1984	Anaheim, CA, USA	Thermal Reduction and Separation	Not specified	60% of battery packs	Continue efficient recycling practices
Ascend Elements	2015	Westborough, MA, USA	Hydro-to-Cathode Direct Precursor Synthesis	Honda, Jaguar, Land Rover, Orbia, Fluorinated Solutions	30,000 tons	Supply more than 5000 tons per year

* Values originally presented in gigawatt-hours (GWh) were transformed into metric tons based on an assumed average energy density of 0.2 kilowatt-hours per kilogram (kWh/kg). ** NJIT, Rutgers, Princeton University, Argonne National Laboratory, NREL, Oak Ridge Lab, UC Irvine, PNNL, Greenland, Cenntro, Traxys. *** While NJIT has ties with Princeton NuEnergy, this relationship has not influenced the results of this research, and there has been no direct engagement with the company during this study. ^ The cryogenic method is a novel and evolving technique for recycling lithium-ion batteries. It utilizes low temperatures to render battery components such as the PVDF binder brittle for easy crushing and separation. This physical processing approach stands out from traditional recycling methods—such as pyrometallurgy, hydrometallurgy, and direct recycling—by improving material purity and minimizing chemical use [100]. ^^ Exclusively developed by Princeton NuEnergy, the LPAS™ technology is a unique approach to recycling lithium-ion batteries, encompassing batteries from both electric vehicles and consumer electronics. PNE's proprietary process stands out by enabling the repair and regeneration of cathode and anode materials without completely decomposing their chemical structures. This method significantly cuts down on energy and chemical use and is an eco-friendlier and more cost-efficient alternative to traditional recycling methods [101].

9. Conclusions

Given the critical evolution of lithium battery recycling by advanced methodologies such as hydrometallurgy and pyrometallurgy, industry leaders such as Redwood Materials, ABTC, Ecobat, and Li-Cycle, recover substantial amounts of valuable metal. These entities not only affirm the commercial viability and efficiency of these processes, with recovery rates soaring above 95%, but also highlight the meticulous compliance required with stringent transportation and safety standards, such as the UN 38.3 Certification and DOT packaging requirements. This adherence ensures the secure handling of lithium-ion batteries (LIBs), classified as hazardous materials, thereby prioritizing human and environmental safety.

In a broader context, the escalating demand for electric vehicle (EV) battery capacity, projected to surge from 120 GWh in 2019 to approximately 680 GWh by 2025, also emphasizes the urgency for scalable recycling solutions. This demand amplifies the significance of the recycling industry's capacity, currently under 100,000 metric tons annually, at fewer than a dozen major facilities globally. Moreover, the strategic emphasis on recycling is highlighted by China's dominance in EV battery production and recycling, projecting a market expansion from $11 billion in 2022 to $18 billion by 2028. With projections indicating the recycling of 900 kilotons of lithium-ion batteries (LIBs) by 2025, recyclers are poised to make a substantial profit. American recycling firms, in particular, are setting their sights on reshaping the competitive landscape, aiming ambitiously to surpass China's current dominance and establish the United States as the global leader in battery recycling. This analysis underlines not only the substantial environmental and economic benefits of recycling LIBs but also the critical need for investment in the development and expansion of EV battery recycling facilities to foster resource conservation and mitigate pollution.

The future trends, challenges, and opportunities of the second-use of lithium-ion battery (LIB) highlight a complex interplay between technological advancements, regulatory frameworks, and circular economy principles. The global outlook on LIB recycling practices underscores the urgency of addressing environmental impacts through cleaner energy sources and innovative recycling technologies, aiming for a significant reduction in the demand for raw materials and emissions associated with LIB production. Circular economy models proposed a shift towards sustainable, closed-loop systems, emphasizing the recovery of valuable metals and the repurposing of LIBs for second-life applications, despite current low recycling rates and challenges in achieving high recovery rates for critical materials. Technological and logistical challenges persist, including the need for optimized recycling, innovative repair technologies, and harmonization of testing standards to ensure safety and efficiency. Regulatory frameworks are evolving to support LIB repair and reuse, with an emphasis on extending the usage cycle of battery systems and developing technologies that minimize environmental pollution and costs. The adoption of these strategies faces economic viability concerns, technological hurdles, and regulatory barriers, necessitating continuous innovation and supportive policies to overcome obstacles and unlock the potential benefits of LIB reuse and recycling for sustainable mobility.

Author Contributions: Conceptualization, J.M.; methodology, J.M. and D.W.; validation, J.M., D.W. and G.C.; formal analysis, J.M. and G.C.; investigation, G.C.; writing—original draft preparation, G.C.; writing—review and editing, J.M., D.W. and G.C.; supervision, J.M.; project administration, J.M.; funding acquisition, J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the New Jersey Department of Environmental Protection, grant number SHW23-003, and titled "Sustainable Management of Rechargeable Batteries used in Electric Vehicles in NJ".

Data Availability Statement: No new data were created. No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect views or policies of NJIT or NJDEP. This paper does not constitute a standard, specification, or regulation. The authors wish to acknowledge the efforts of the NJDEP project Riley Kirejevas and Chris Mikulewicz, as well as the contributions of Siddhartha Chittineni and Vaidehi Gandhi of NJIT, and Sarvagna Malladi, a NJIT Provost Highschool Scholar. The AI software ChatGPT version 3.4 was used to rephrase and improve the presentation of this article but not the content.

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

References

1. Fischer, J. Electric Vehicle Sales and Market Share. CarEdge. 20 October 2023. Available online: https://caredge.com/guides/electric-vehicle-market-share-and-sales (accessed on 20 April 2024).
2. Meegoda, J.N.; Malladi, S.; Zayas, I.C. End-of-Life Management of Electric Vehicle Lithium-Ion Batteries in the United States. *Clean Technol.* **2022**, *4*, 1162–1174. [CrossRef]
3. Flash Battery. Lithium Battery Transport: All You Need to Know. 2022. Available online: https://www.flashbattery.tech/en/lithium-battery-transport/ (accessed on 20 April 2024).
4. Agnihotri, N. What Battery Chemistries Are Used in Electric Vehicles? Engineers Garage. 2023. Available online: https://www.engineersgarage.com/ev-battery-chemistries-ncm-lfp-nca-lmo-lto-lco/ (accessed on 20 April 2024).
5. Väyrynen, A.; Salminen, J. Lithium ion battery production. *J. Chem. Thermodyn.* **2012**, *46*, 80–85. [CrossRef]
6. Kurland, S.D. Energy use for GWh-scale lithium-ion battery production. *Environ. Res. Commun.* **2019**, *2*, 012001. [CrossRef]
7. Gaines, L.; Sullivan, J.; Burnham, A.; Belharouak, I. Life-cycle analysis for lithium-ion battery production and recycling. In Proceedings of the Transportation Research Board 90th Annual Meeting, Washington, DC, USA, 23–27 January 2011; pp. 23–27.
8. Chordia, M.; Nordelöf, A.; Ellingsen, L.A.W. Environmental life cycle implications of upscaling lithium-ion battery production. *Int. J. Life Cycle Assess.* **2021**, *26*, 2024–2039. [CrossRef]
9. Romare, M.; Dahllöf, L. The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. 2017. Available online: https://www.energimyndigheten.se/49c5dc/globalassets/forskning--innovation/transporter/c243-the-life-cycle-energy-consumption-and-co2-emissions-from-lithium-ion-batteries-.pdf (accessed on 20 April 2024).
10. EPA. Resource Conservation and Recovery Act (RCRA) Laws and Regulations. RCRA. 2023. Available online: https://www.epa.gov/rcra (accessed on 20 April 2024).
11. Bill S3723. New Jersey Legislature. 2023. Available online: https://www.njleg.state.nj.us/bill-search/2022/S3723/bill-text?f=S4000&n=3723_I1 (accessed on 20 April 2024).
12. United Nations. Transport of Dangerous Goods—UNECE. 2019. Available online: https://unece.org/fileadmin/DAM/trans/danger/publi/unrec/rev21/ST-SG-AC10-1r21e_Vol1_WEB.pdf (accessed on 20 April 2024).
13. UNECE. Recommendations on the Transport of Dangerous Goods. UN 38.3 Certification. 2015. Available online: https://unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev.6/1520832_E_ST_SG_AC.10_11_Rev6_WEB_-With_corrections_from_Corr.1.pdf (accessed on 20 April 2024).
14. UN 38.3 Transportation Testing for Lithium-Ion Batteries. Southwest Research Institute. 6 December 2023. Available online: https://www.swri.org/industry/battery-testing-research/un-383-transportation-testing-lithium-ion-batteries (accessed on 20 April 2024).
15. PHMSA. Transporting Lithium Batteries. 2021. Available online: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2021-09/Lithium-Battery-Guide.pdf (accessed on 20 April 2024).
16. Intergovernmental Organisation for International Carriage by Rail. RID 2023. OTIF Intergovernmental Organisation for International Carriage by Rail iCal. 2023. Available online: https://otif.org/en/?page_id=1105 (accessed on 20 April 2024).
17. UNECE. ADR 2023—Agreement Concerning the International Carriage of Dangerous Goods by Road. 2023. Available online: https://unece.org/transport/standards/transport/dangerous-goods/adr-2023-agreement-concerning-international-carriage (accessed on 20 April 2024).
18. UNECE. European Agreement Concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN). 2021. Available online: https://unece.org/transport/documents/2021/01/european-agreement-concerning-international-carriage-dangerous-goods (accessed on 20 April 2024).
19. International Maritime Organization. The International Maritime Dangerous Goods (IMDG) Code. 2019. Available online: https://www.imo.org/en/OurWork/Safety/Pages/DangerousGoods-default.aspx (accessed on 20 April 2024).
20. IATA. Dangerous Goods Regulations (DGR). 2024. Available online: https://www.iata.org/en/publications/dgr/ (accessed on 20 April 2024).
21. USEPA. Environmental Laws That Apply to Mercury | US EPA. The Mercury-Containing and Rechargeable Battery Management Act—Public Law 104-142. 1996. Available online: https://www.epa.gov/mercury/environmental-laws-apply-mercury (accessed on 20 April 2024).
22. Thompson Safety. How Do You Put Out a Lithium-Ion Fire? 2023. Available online: https://thompson-safety.com/company/press/lithium-ion-battery-fire (accessed on 20 April 2024).
23. EV Resource. Burning Issues: The Truth about EV Battery Fires. 2023. Available online: https://www.ev-resource.com/articles/burning-issues-the-truth-about-ev-battery-fires-part-one#/ (accessed on 20 April 2024).

24. NFPA. Lithium-Ion Battery Safety. 2023. Available online: https://www.nfpa.org/education-and-research/home-fire-safety/lithium-ion-batteries (accessed on 20 April 2024).
25. Lugo, R. You're Wrong about EV Fires. MotorTrend. 2023. Available online: https://www.motortrend.com/features/you-are-wrong-about-ev-fires/ (accessed on 20 April 2024).
26. Abdul. Electric Cars in Sweden: A Growing Trend. OS Vehicles. 2022. Available online: https://www.osvehicle.com/electric-cars-in-sweden-a-growing-trend/ (accessed on 20 April 2024).
27. USFA. Electric Vehicle Fire Safety. U.S. Fire Administration. 2023. Available online: https://www.usfa.fema.gov/prevention/vehicle-fires/electric-vehicles (accessed on 20 April 2024).
28. The Maritime Executive. Lithium-Ion Battery Fire Contained Aboard Bulker off Dutch Harbor. 31 December 2023. Available online: https://maritime-executive.com/article/lithium-ion-battery-fire-contained-aboard-bulker-off-dutch-harbor (accessed on 20 April 2024).
29. National Transportation Safety Board. Lithium-Ion Battery Explosion Leads to Fire on Oil Tanker. NTSB. 13 November 2022. Available online: https://www.ntsb.gov/news/press-releases/Pages/NR20231109.aspx (accessed on 20 April 2024).
30. ROI-NJ. Bill Aims to Help N.J. Be Leader in Recycling of EV Batteries. ROI. 17 May 2023. Available online: https://www.roi-nj.com/2023/05/16/industry/energy-utilities/bill-aims-to-help-n-j-be-leader-in-recycling-of-ev-batteries/ (accessed on 20 April 2024).
31. Washington State Department of Ecology. Battery Stewardship. Battery Stewardship. 2023. Available online: https://ecology.wa.gov/waste-toxics/reducing-recycling-waste/our-recycling-programs/battery-stewardship (accessed on 20 April 2024).
32. Dunn, J. California's Progress toward Recycling Policy for EV Batteries. The Equation. 20 September 2022. Available online: https://blog.ucsusa.org/jessica-dunn/californias-progress-toward-recycling-policy-for-ev-batteries/ (accessed on 20 April 2024).
33. Greentec Auto. Hybrid Battery Repair Shop in New Jersey. 2023. Available online: https://www.greentecauto.com/locations/new-jersey (accessed on 20 April 2024).
34. The United States Government. Inflation Reduction Act Guidebook. The White House. 5 December 2023. Available online: https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/ (accessed on 20 April 2024).
35. CRANE. Battery Logistics: Shipping, Storage and Transportation—Crane Worldwide Logistics. Crane Worldwide. 2023. Available online: https://www.craneww.com/solutions/battery-logistics/ (accessed on 20 April 2024).
36. ReCell. Direct Recycling of Materials. Direct Recycling of Materials—Recell Center. 2023. Available online: https://recellcenter.org/research/direct-recycling-of-materials/ (accessed on 20 April 2024).
37. Global Battery Alliance. Establishing a Sustainable and Responsible Battery Value Chain. Global Battery Alliance, GBA. 2023. Available online: https://www.globalbattery.org/ (accessed on 20 April 2024).
38. Hendrickson, T.P.; Kavvada, O.; Shah, N.; Sathre, R.; Scown, C.D. Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California. *Environ. Res. Lett.* **2015**, *10*, 014011. [CrossRef]
39. Slattery, M.; Dunn, J.; Kendall, A. Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resour. Conserv. Recycl.* **2021**, *174*, 105755. [CrossRef]
40. Tailor-Made Solutions for End-of-Life EV-Batteries. Reneos. 2023. Available online: https://www.reneos.eu/case/how-battery-repair-centres-extend-the-life-cycle-of-ev-batteries (accessed on 20 April 2024).
41. Stone, M.; Grist. EV Batteries Are Dangerous to Repair. Here's Why Mechanics Are Doing so Anyway. Scientific American. 15 December 2023. Available online: https://www.scientificamerican.com/article/ev-batteries-are-dangerous-to-repair-heres-why-mechanics-are-doing-so-anyway/ (accessed on 20 April 2024).
42. EPA. Subject: Lithium Battery Recycling Regulatory Status and Frequently Asked Questions from. 2023. Available online: https://rcrapublic.epa.gov/files/14957.pdf (accessed on 20 April 2024).
43. Bi, H.; Zhu, H.; Zu, L.; Gao, Y.; Gao, S.; Bai, Y. Environment-friendly technology for recovering cathode materials from spent lithium iron phosphate batteries. *Waste Manag. Res.* **2020**, *38*, 911–920. [CrossRef]
44. Sun, L.Y.; Liu, B.R.; Wu, T.; Wang, G.G.; Huang, Q.; Su, Y.F.; Wu, F. Hydrometallurgical recycling of valuable metals from spent lithium-ion batteries by reductive leaching with stannous chloride. *Int. J. Miner. Metall. Mater.* **2021**, *28*, 991–1000. [CrossRef]
45. Lin, J.; Wu, J.; Fan, E.; Zhang, X.; Chen, R.; Wu, F.; Li, L. Environmental and economic assessment of structural repair technologies for spent lithium-ion battery cathode materials. *Int. J. Miner. Metall. Mater.* **2022**, *29*, 942–952. [CrossRef]
46. Nie, H.; Xu, L.; Song, D.; Song, J.; Shi, X.; Wang, X.; Zhang, L.; Yuan, Z. $LiCoO_2$: Recycling from spent batteries and regeneration with solid state synthesis. *Green Chem.* **2015**, *17*, 1276–1280. [CrossRef]
47. Nenadic, N.G.; Trabold, T.A.; Thurston, M.G. Cell Replacement Strategies for Lithium Ion Battery Packs. *Batteries* **2020**, *6*, 39. [CrossRef]
48. International Electrotechnical Commission, Geneva, Switzerland (IEC). Redline Version International Standard—IEC. 2018. Available online: https://webstore.iec.ch/preview/info_iec62660-1%7Bed2.0.RLV%7Den.pdf (accessed on 20 April 2024).
49. *ISO 12405-1:2011*; International Organization for Standardization: Geneva, Switzerland, 2018. Available online: https://www.iso.org/standard/51414.html (accessed on 20 April 2024).
50. SAE International, Pennsylvania, United States. J2464_202108: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing. 2021. Available online: https://www.sae.org/standards/content/j2464_202108/ (accessed on 20 April 2024).

51. *IEC 62660-3:2022*; International Electrotechnical Commission: Geneva, Switzerland, 2022. Available online: https://webstore.iec.ch/publication/65084 (accessed on 20 April 2024).
52. Fan, Z.; Xing, Z.-X.; Wu, M.-H. State of Health Estimation for li-ion battery using characteristic voltage intervals and genetic algorithm optimized back propagation neural network. *J. Energy Storage* **2023**, *57*, 106277. [CrossRef]
53. Andrea, D. *Battery Management Systems for Large Lithium-Ion Battery Packs*; Artech House: London, UK, 2010.
54. Neubauer, J.; Wood, E. The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility. *J. Power Sources* **2014**, *257*, 12–20. [CrossRef]
55. Tomaszewska, A.; Chu, Z.; Feng, X.; O'kane, S.; Liu, X.; Chen, J.; Ji, C.; Endler, E.; Li, R.; Liu, L.; et al. Lithium-ion battery fast charging: A review. *eTransportation* **2019**, *1*, 100011. [CrossRef]
56. Tanim, T.R.; Dufek, E.J.; Evans, M.; Dickerson, C.; Jansen, A.N.; Polzin, B.J.; Dunlop, A.R.; Trask, S.E.; Jackman, R.; Bloom, I.; et al. Extreme fast charge challenges for lithium-ion battery: Variability and positive electrode issues. *J. Electrochem. Soc.* **2019**, *166*, A1926. [CrossRef]
57. Lu, J.; Wu, T.; Amine, K. State-of-the-art characterization techniques for advanced lithium-ion batteries. *Nat. Energy* **2017**, *2*, 17011. [CrossRef]
58. Paul, P.P.; McShane, E.J.; Colclasure, A.M.; Balsara, N.; Brown, D.E.; Cao, C.; Chen, B.R.; Chinnam, P.R.; Cui, Y.; Dufek, E.J.; et al. A review of existing and emerging methods for lithium detection and characterization in Li-ion and Li-metal batteries. *Adv. Energy Mater.* **2021**, *11*, 2100372. [CrossRef]
59. Hatzell, K.B.; Chen, X.C.; Cobb, C.L.; Dasgupta, N.P.; Dixit, M.B.; Marbella, L.E.; McDowell, M.T.; Mukherjee, P.P.; Verma, A.; Viswanathan, V.; et al. Challenges in lithium metal anodes for solid-state batteries. *ACS Energy Lett.* **2020**, *5*, 922–934. [CrossRef]
60. Albertus, P.; Babinec, S.; Litzelman, S.; Newman, A. Status and challenges in enabling the lithium metal electrode for high-energy and low-cost rechargeable batteries. *Nat. Energy* **2018**, *3*, 16–21. [CrossRef]
61. *IEC 62133-1:2017*; International Electrotechnical Commission: Geneva, Switzerland, 2017. Available online: https://webstore.iec.ch/publication/27284 (accessed on 20 April 2024).
62. *IEC 62133-2:2017*; International Electrotechnical Commission: Geneva, Switzerland, 2017. Available online: https://webstore.iec.ch/publication/32662 (accessed on 20 April 2024).
63. Copeland, J. Globally-Harmonized Battery Safety Standards. In Compliance Magazine. 2018. Available online: https://incompliancemag.com/globally-harmonized-battery-safety-standards/ (accessed on 20 April 2024).
64. Kelleher. Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles. 2019. Available online: https://www.api.org/~/media/Files/Oil-and-Natural-Gas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf (accessed on 20 April 2024).
65. Kotak, Y.; Marchante Fernández, C.; Canals Casals, L.; Kotak, B.S.; Koch, D.; Geisbauer, C.; Trilla, L.; Gómez-Núñez, A.; Schweiger, H.G. End of Electric Vehicle Batteries: Reuse vs. Recycle. *Energies* **2021**, *14*, 2217. [CrossRef]
66. Morales, J. How Much Does It Cost to Replace a Tesla Battery? (And Can You Do It Yourself?). MUO. 25 March 2023. Available online: https://www.makeuseof.com/how-much-cost-replace-tesla-battery/ (accessed on 20 April 2024).
67. The Mobility House, World's Largest 2nd-Use Battery Storage Is Starting Up. 2016. Available online: https://www.mobilityhouse.com/int_en/magazine/press-releases/worlds-largest-2nd-use-battery-storage-is-starting-up.html (accessed on 20 April 2024).
68. 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.* **2017**, *22*, 111–124. [CrossRef]
69. Shahjalal, M.; Roy, P.K.; Shams, T.; Fly, A.; Chowdhury, J.I.; Ahmed, M.R.; Liu, K. A review on second-life of Li-ion batteries: Prospects, challenges, and issues. *Energy* **2022**, *241*, 122881. [CrossRef]
70. Lih, W.C.; Yen, J.H.; Shieh, F.H.; Liao, Y.M. Second use of retired lithium-ion battery packs from electric vehicles: Technological challenges, cost analysis and optimal business model. In Proceedings of the 2012 International Symposium on Computer, Consumer and Control, Taichung, Taiwan, 4–6 June 2012; IEEE: New York, NY, USA, 2012; pp. 381–384.
71. UCSUSA. Electric Vehicle Batteries. Union of Concerned Scientists. 2021. Available online: https://www.ucsusa.org/resources/ev-battery-recycling (accessed on 20 April 2024).
72. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **2019**, *575*, 75–86. [CrossRef] [PubMed]
73. USEPA. Lithium-Ion Battery Recycling | USEPA. 2023. Available online: https://www.epa.gov/hw/lithium-ion-battery-recycling (accessed on 20 April 2024).
74. Newton, E. The Complete Guide to EV Battery Recycling Techniques. Energy Central. 2020. Available online: https://energycentral.com/c/ec/complete-guide-ev-battery-recycling-techniques (accessed on 20 April 2024).
75. Kimani, A. China's EV Sector Will Become Self-Sufficient by 2060. OilPrice.com. 2023. Available online: https://oilprice.com/Energy/Energy-General/Chinas-EV-Sector-Will-Become-Self-Sufficient-By-2060.html (accessed on 20 April 2024).
76. EMR. Global Battery Recycling Market Report and Forecast 2024–2032. Battery Recycling Market Size, Share, Analysis 2024–2032. 2023. Available online: https://www.expertmarketresearch.com/reports/battery-recycling-market (accessed on 20 April 2024).
77. Wesselkämper, J.; Dahrendorf, L.; Mauler, L.; Lux, S.; von Delft, S. A battery value chain independent of primary raw materials: Towards circularity in China, Europe and the US. *Resour. Conserv. Recycl.* **2024**, *201*, 107218. [CrossRef]

78. Carey, N.; Lienert, P.; Waldersee, V. Dead EV Batteries Turn to Gold with US Incentives. 2023. Available online: https://www.reuters.com/business/autos-transportation/dead-ev-batteries-turn-gold-with-us-incentives-2023-07-21/ (accessed on 20 April 2024).
79. Konietzko, J.; Baldassarre, B.; Brown, P.; Bocken, N.; Hultink, E.J. Circular business model experimentation: Demystifying assumptions. *J. Clean. Prod.* **2020**, *277*, 122596. [CrossRef]
80. MacArthur, E. Towards the circular economy. *J. Ind. Ecol.* **2013**, *2*, 23–44.
81. Geissdoerfer, M.; Morioka, S.N.; de Carvalho, M.M.; Evans, S. Business models and supply chains for the circular economy. *J. Clean. Prod.* **2018**, *190*, 712–721. [CrossRef]
82. Choubey, P.K.; Kim, M.S.; Srivastava, R.R.; Lee, J.C.; Lee, J.Y. Advance review on the exploitation of the prominent energy-storage element: Lithium. Part I: From mineral and brine resources. *Miner. Eng.* **2016**, *89*, 119–137. [CrossRef]
83. Invernizzi, D.C.; Locatelli, G.; Velenturf, A.; Love, P.E.; Purnell, P.; Brookes, N.J. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. *Energy Policy* **2020**, *144*, 111677. [CrossRef]
84. Neumann, J.; Petranikova, M.; Meeus, M.; Gamarra, J.D.; Younesi, R.; Winter, M.; Nowak, S. Recycling of lithium-ion batteries—Current state of the art, circular economy, and next generation recycling. *Adv. Energy Mater.* **2022**, *12*, 2102917. [CrossRef]
85. Shanmugam, V.; Das, O.; Neisiany, R.E.; Babu, K.; Singh, S.; Hedenqvist, M.S.; Berto, F.; Ramakrishna, S. Polymer recycling in additive manufacturing: An opportunity for the circular economy. *Mater. Circ. Econ.* **2020**, *2*, 11. [CrossRef]
86. Velázquez-Martínez, O.; Valio, J.; Santasalo-Aarnio, A.; Reuter, M.; Serna-Guerrero, R. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries* **2019**, *5*, 68. [CrossRef]
87. Ahuja, J.; Dawson, L.; Lee, R. A circular economy for electric vehicle batteries: Driving the change. *J. Prop. Plan. Environ. Law* **2020**, *12*, 235–250. [CrossRef]
88. Fujita, T.; Chen, H.; Wang, K.T.; He, C.L.; Wang, Y.B.; Dodbiba, G.; Wei, Y.Z. Reduction, reuse and recycle of spent Li-ion batteries for automobiles: A review. *Int. J. Miner. Metall. Mater.* **2021**, *28*, 179–192. [CrossRef]
89. Mossali, E.; Picone, N.; Gentilini, L.; Rodrìguez, O.; Pérez, J.M.; Colledani, M. Lithium-ion batteries towards Circular Economy: A literature review of opportunities and issues of recycling treatments. *J. Environ. Manag.* **2020**, *264*, 110500. [CrossRef]
90. Alizadeh Sahraei, A.; Azizi, D.; Mokarizadeh, A.H.; Boffito, D.C.; Larachi, F. Emerging trends of computational chemistry and molecular modeling in froth flotation: A Review. *ACS Eng. Au* **2023**, *3*, 128–164. [CrossRef]
91. Zhou, L.-F.; Yang, D.; Du, T.; Gong, H.; Luo, W.-B. The current process for the recycling of spent lithium ion batteries. *Front. Chem.* **2020**, *8*, 578044. [CrossRef]
92. Folayan, T.-O.; Lipson, A.L.; Durham, J.L.; Pinegar, H.; Liu, D.; Pan, L. Direct recycling of blended cathode materials by froth flotation. *Energy Technol.* **2021**, *9*, 2100468. [CrossRef]
93. Kelleher. 7 Factors Affecting Froth Flotation Process. JXSC Machine. 2018. Available online: https://www.jxscmachine.com/new/7-factors-affecting-froth-flotation/ (accessed on 20 April 2024).
94. He, M.; Jin, X.; Zhang, X.; Duan, X.; Zhang, P.; Teng, L.; Liu, Q.; Liu, W. Combined pyro-hydrometallurgical technology for recovering valuable metal elements from spent lithium-ion batteries: A review of recent developments. *Green Chem.* **2023**, *25*, 6561–6580. [CrossRef]
95. Enuh, B.M. Advanced Battery Material Recycling Technology. AZoM.com. 2023. Available online: https://www.azom.com/article.aspx?ArticleID=22300 (accessed on 20 April 2024).
96. Zhan, R.; Oldenburg, Z.; Pan, L. Recovery of active cathode materials from lithium-ion batteries using froth flotation. *Sustain. Mater. Technol.* **2018**, *17*, e00062. [CrossRef]
97. Rensmo, A.; Savvidou, E.K.; Cousins, I.T.; Hu, X.; Schellenberger, S.; Benskin, J.P. Lithium-ion battery recycling: A source of per-and polyfluoroalkyl substances (PFAS) to the environment? *Environ. Sci. Process. Impacts* **2023**, *25*, 1015–1030. [CrossRef] [PubMed]
98. Dai, Q.; Spangenberger, J.; Ahmed, S.; Gaines, L.; Kelly, J.C.; Wang, M. *EverBatt: A Closed-Loop Battery Recycling Cost and Environmental Impacts Model*; (No. ANL-19/16); Argonne National Lab. (ANL): Argonne, IL, USA, 2019.
99. Breiter, A.; Linder, M.; Schuldt, T.; Siccardo, G.; Vekić, N. Battery Recycling Takes the Driver's Seat. McKinsey & Company. 13 March 2023. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat#/ (accessed on 20 April 2024).
100. Bhar, M.; Ghosh, S.; Krishnamurthy, S.; Kaliprasad, Y.; Martha, S.K. A review on spent lithium-ion battery recycling: From collection to black mass recovery. *RSC Sustain.* **2023**, *1*, 1150–1167. [CrossRef]
101. Princeton NuEnergy. PNE Novel Plasma-Based Recycling Technology. 17 July 2023. Available online: https://pnecycle.com/pne-novel-plasma-based-recycling-technology/ (accessed on 20 April 2024).