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Review

Pathways to Circular Economy for Electric Vehicle Batteries

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Abstract: The global shift towards sustainability is driving the electrification of transportation and the adoption of clean energy storage solutions, moving away from internal combustion engines. This transition significantly impacts lithium-ion battery production in the electric vehicle (EV) market. This paper summarizes specialized topics to highlight regional differences and specific challenges related to electric batteries, focusing on how pollution from gas consumption, distribution, usage, and lithium production affects society. EV batteries offer promising opportunities for a sustainable future, considering their economic and environmental impacts and the importance of understanding their lifecycle. This analysis delves into the recovery of materials and various methods for extracting lithium and manufacturing EV batteries. Efficient lithium recovery is crucial and globally significant, with liquid extraction presenting a more environmentally friendly option. By addressing these challenges, this paper provides an overview of the rationale behind supporting the future of EVs.

Keywords: circular economy; Li-ion battery; recovery; recycling; reuse

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1. Introduction

1.1. Overview of Electric Vehicles and Battery Technology

Electric vehicle (EV) batteries are rapidly becoming one of the most significant products of our time. As the climate crisis intensifies, it is imperative to find solutions that reduce greenhouse gas emissions. Traditional vehicles with internal combustion engines are major contributors to these emissions. In contrast, EVs are seen as a viable alternative since they emit no greenhouse gases during operation. The key to enabling EVs to function without internal combustion engines lies in the battery. The lithium-ion battery is the most popular choice for EVs due to its compact size, lightweight nature, and extremely high energy density [1]. Optimizing lithium-ion battery technology is crucial for enhancing the efficiency and performance of EVs, paving the way for a sustainable future.

1.1.1. Growth of the Electric Vehicle Market

The demand for EVs is rapidly increasing and is projected to soar in the coming decades, as illustrated in Figure 1. The global electric vehicle market is expected to grow significantly over the next decade. According to the International Energy Agency (IEA), the number of electric vehicles on the road is projected to reach 145 million by 2030 under current policy scenarios, with the potential to reach 230 million in an accelerated scenario. This growth is driven by government policies, declining battery costs, and increased consumer demand for cleaner transportation options [2]. Several factors contribute to this trend, with financial incentives being a major driving force. Initially, EVs were prohibitively expensive, but as technology has advanced and manufacturing processes have become more efficient, costs have steadily decreased. Additionally, the unreliability and rising costs of gasoline make EVs an increasingly attractive option, despite their higher upfront

cost [3,4]. Moreover, societal trends are shifting towards greater environmental consciousness. Many people are becoming more aware of their contributions to climate change and feel good about driving vehicles with a reduced carbon footprint [5]. Many countries are aiming to reduce or eliminate the production of traditional vehicles while encouraging the manufacturing and adoption of EVs. The UK, France, Germany, the Netherlands, and several other countries have committed to the objectives of the Paris Agreement and are developing strategies to phase out the production of internal combustion engine vehicles (ICEVs) by 2040 [6]. Governments are also introducing supportive measures, such as purchase incentives and electricity subsidies, to encourage consumers to choose electric vehicles (EVs) in countries like Japan, Germany, Finland, France, and Austria [7,8]. These factors collectively suggest that the demand for EVs will continue to grow, reinforcing the positive outlook for the EV market [9].

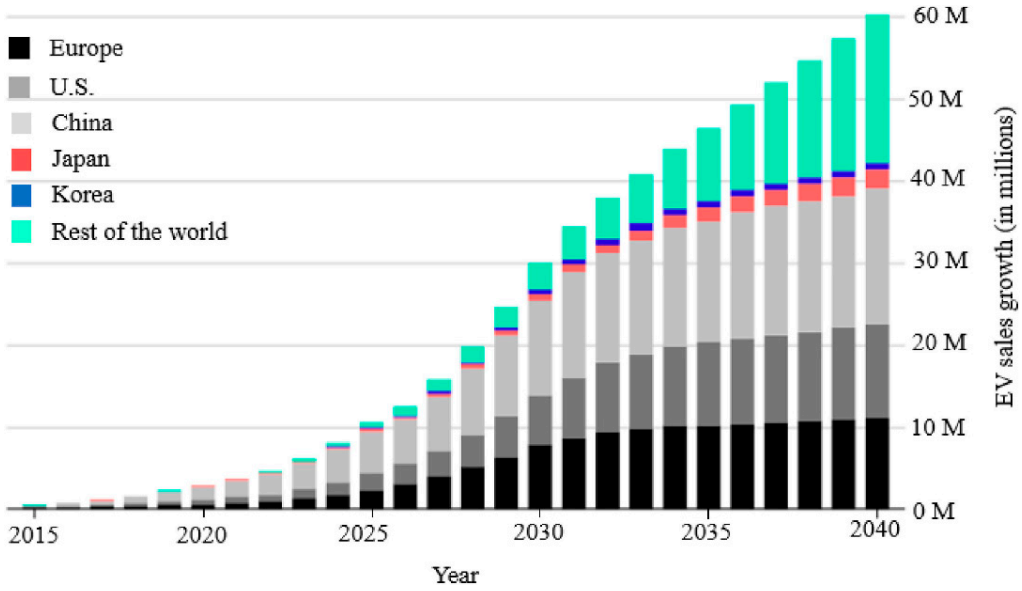


Figure 1. Global sales growth and demand for EVs (reproduced with permission from [10]).

1.1.2. Importance of Batteries in Electric Vehicles

An EV relies entirely on its battery to operate, allowing it to charge and run without an internal combustion engine. While gas-powered vehicles use fuel combustion to generate power, EVs use batteries that convert stored chemical energy into a continuous flow of electrical energy to drive the vehicle [11]. Consequently, the rising demand for EVs directly translates to an increased demand for batteries. The growth in lithium battery demand has been remarkable. In 2010, the demand was approximately 0.5 gigawatt-hours, which surged to 526 gigawatt-hours by 2020 and is projected to reach 9300 gigawatt-hours by 2030 [12]. Lithium batteries are highly appealing due to their ability to store and discharge large amounts of energy over extended periods with relatively low maintenance. These batteries are the cornerstone of EV functionality, necessitating ongoing research to enhance efficiency and optimize their production, usage, and end-of-life management.

1.2. End-of-Life Challenges for Electric Vehicle Batteries

One of the main challenges with large-scale battery use is managing their end-of-life phase. Although this issue has been relatively minor so far owing to the long lifespan of lithium-ion batteries and the recent surge in production over the past decade, it is expected to become significant around 2030 [13]. This is when many of the batteries produced in the last 5–10 years will start to reach the end of their useful life [14]. Fortunately, advances in battery recycling technology are being developed to address this impending challenge. The key will be integrating various recycling systems to ensure a smooth transition through the different stages of a battery's lifecycle, from production to end-of-life management.

1.2.1. Environmental Impact of Disposal

The demand for disposing of EV batteries has surged, attracting significant interest from companies. EV batteries contain rare minerals and materials that are difficult to source, making the recycling process complex. While recycling is essential for nonfunctional or broken batteries, lithium-ion batteries can also be repurposed for other powerful applications, such as solar panels or power generators. These practices are more environmentally friendly than extracting new materials [15]. Although old EV batteries may no longer be suitable for vehicle use, they can still be repurposed in other fields, extending their lifespan and providing additional value.

1.2.2. Resource Recovery Opportunities

The need to conserve and recover valuable minerals from old EV batteries is increasing, helping to minimize environmental impact and promote a more sustainable future. Understanding the lifecycle of EVs and the process of mineral recovery is crucial, as it influences recycling practices and recovery methods. By optimizing these processes, we can reduce waste, minimize resource extraction, and lower carbon emissions [16]. This not only creates economic opportunities but also aligns global interests towards the production of cleaner energy.

1.3. Circular Economy Principles and Their Application

The concept of a circular economy focuses on reusing existing materials and products for as long as possible to reduce the need for raw materials and minimize environmental impact. Figure 2 illustrates the ideal lifecycle of a material within this framework. This approach can be applied across all economic sectors, primarily through recycling or repurposing materials. The benefits are significant: less waste production, reduced raw material extraction, and long-term cost savings. However, the widespread implementation of a circular economy is limited by current technological constraints and the lack of established processes for effectively recycling or repurposing many products. Developing these technologies and systems is crucial for expanding the circular economy across all sectors [17].



Figure 2. Circular economy model [18].

1.3.1. Circular Economy in the Context of EV Batteries

EV batteries exemplify how products can fit into a circular economy, primarily due to the valuable materials used in their construction. The lifecycle of EV batteries begins with the mining of rare raw materials such as lithium, cobalt, and nickel [19]. These materials are then used in the manufacturing process to create the batteries. With an average lifespan of 10–15 years, the critical question is what happens to these batteries at the end of their life [20]. By applying the principles of a circular economy, the materials from spent batteries can be stripped down and recovered. These reclaimed materials can then be used to manufacture new batteries, reducing the need for fresh raw material extraction. This process not only cuts down costs but also enhances efficiency and sustainability [21].

1.3.2. Objectives and Scope of the Review

The primary objective of this review is to explore pathways to a circular economy for EV batteries. This involves examining the properties and lifecycle of the batteries to understand their societal and environmental impacts and the importance of alternative end-of-life solutions. The review will then analyze how to implement circular economy practices within the lifecycle of EV batteries, including the necessary technologies. Additionally, it will discuss the potential environmental and societal impacts, existing challenges, and barriers that must be addressed. Finally, the review will outline what is needed for this approach to shape the future.

2. Lifecycle of Electric Vehicle Batteries

2.1. Battery Composition and Materials

When discussing EVs, it is important to recognize that various battery types are used, depending on manufacturer preference. The four main battery types used in EVs are lithium-ion, nickel-metal hydride, lead-acid, and ultracapacitor batteries [22]. For this paper, the focus will specifically be on lithium-ion batteries, as they are the most commonly used in the EV industry today. Lithium-ion batteries are preferred in the EV industry due to their long service life, manageable temperature range, and high energy efficiency relative to their physical size [23]. These characteristics make them ideal for a circular economy, as their longevity reduces the need for frequent replacements, thereby decreasing long-term material demand. However, the increasing prevalence of EVs, driven by a global shift towards reducing carbon footprints and enhancing sustainability, has led to a corresponding rise in lithium-ion battery production [24]. This increased production can counteract the reduced material demand benefits typically associated with the batteries' long lifespan [25]. Understanding the detailed properties and lifecycle of lithium-ion batteries is crucial for integrating them into a circular economy model. This knowledge allows for the development of more efficient recycling and repurposing practices, ultimately supporting sustainability goals.

2.1.1. Overview of Battery Components

Lithium-ion batteries consist of four main components: the anode, cathode, electrolyte, and separator. The anode is the negative electrode, and the cathode is the positive electrode. These electrodes work together, with the anode releasing excess electrons into the external circuit while the cathode draws them in. The electrolyte serves as the medium through which electrons are transferred between the anode and cathode. Finally, the separator keeps the anode and cathode apart, preventing short circuits and helping regulate the strength of the electric current [25]. A schematic view of the battery is shown in Figure 3.

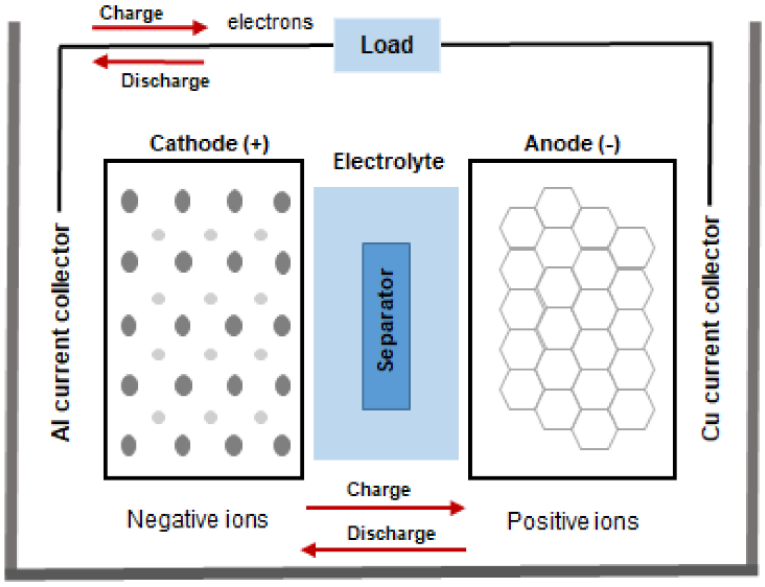


Figure 3. A schematic diagram shows the lithium−ion battery's components and working [26].

2.1.2. Identification of Critical Materials

When discussing the role of EV batteries in a circular economy, the first stage focuses on materials. The raw materials required to make a lithium-ion battery typically include metals such as lithium (with variations in alloys), manganese, copper, graphite, cobalt, nickel, and iron [27]. Figure 4 illustrates the composition of these materials within the overall battery [28]. These metals are chosen for their efficient properties, like conductivity and availability. However, not all materials required for these batteries are economically advantageous to obtain. For instance, cobalt can be expensive because it often needs to be sourced from unstable regions. Despite the cost, cobalt's properties are crucial for better temperature management within the battery, making it difficult to find suitable alternatives [29].

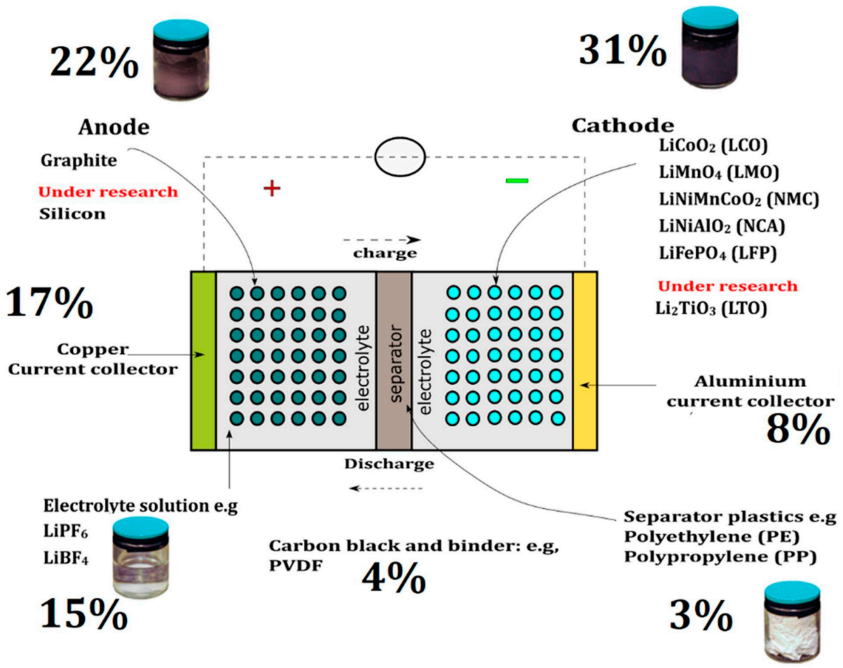


Figure 4. Schematic diagram showing the various components of a lithium-ion battery (reproduced with permission from [30]).

2.2. Manufacturing and Use Phase

The manufacturing process for lithium-ion batteries begins with the selection of their cell type, which can be cylindrical, pouch, or prismatic. In the EV industry, cylindrical cells are typically used. The manufacturing process consists of three main stages: electrode preparation, cell assembly, and battery electrochemistry activation [31]. During the electrode preparation stage, a slurry is created from an active material, a conductive additive, and a binder. The active material, which facilitates chemical reactions that release electrons, can include lithium cobalt for lithium-ion batteries [32]. The conductive additive, often graphite, enhances electron flow between the cathode and anode [33]. The binder, usually a type of polymer, holds the active material and conductive additive together, functioning like glue [34]. The cell assembly stage involves assembling all the battery components into the final cell structure, ensuring it is ready for installation. The final stage, battery electrochemistry activation, involves cycling the battery to establish electrical flow throughout its components, effectively jump-starting its service life [35].

2.2.1. Environmental Impact during Production

The prevalence of EVs has surged in recent years. In an effort to reduce emissions and promote sustainable living practices, transportation has become a key area for implementing these standards, both on individual and governmental levels. However, this growth in EVs brings forth discussions about the environmental impact of their production, particularly the production of the lithium-ion batteries they require. This raises questions about the potential contradictions between the goal of creating a cleaner environment and the environmental footprint of battery production.

An important aspect to consider in the production stages of lithium-ion batteries is the environmental impact of raw material extraction. As previously mentioned, the materials used in lithium-ion batteries include various metals and alloys, which are natural resources. Extracting these materials requires a significant amount of energy, contributing substantially to the environmental impact of lithium-ion battery production [36]. The primary concern with this energy consumption is the associated carbon dioxide emissions. There is a positive correlation between the extraction of natural resources, carbon dioxide emissions, and the ecological footprint. This means that as the mining of natural resources increases, so too do carbon dioxide emissions and the ecological footprint [36]. The ecological footprint measures the amount of land required to sustain the demand for these resources. In summary, increased extraction of natural resources, such as the metals and alloys needed for lithium-ion batteries, leads to greater negative environmental impacts.

Another significant environmental impact of lithium-ion battery production comes from material preparation. After raw materials are extracted, they must undergo various processes before being incorporated into the final battery structure. These processes include sintering, grinding, spraying, coating, drying, and sieving. Each of these steps consumes a substantial amount of energy and resources, such as natural gas, to be carried out effectively [37].

Lastly, the electrode preparation stage in the production of lithium-ion batteries also significantly impacts the environment. During this stage, a slurry is created from active material, a conductive additive, and a binder. This process inevitably releases toxic vapors into the air through chemical reactions. Due to the known toxicity of these vapors, regulations are in place to contain them and prevent their release into the external environment [38].

Overall, the production of lithium-ion batteries for EVs has several negative environmental impacts. These include increased extraction of natural resources, higher carbon dioxide emissions, elevated energy consumption, and the creation of toxic vapors. While EVs are often seen as environmentally beneficial, the environmental effects of battery production can counteract this perception. It is crucial to consider these impacts across the different stages of production to fully understand the environmental footprint of EV batteries.

2.2.2. Considerations during the Operational Life of EV Batteries

Following the production stage, the next phase in the lifecycle of EV lithium-ion batteries is their operational life. This stage involves the actual use of the batteries within EVs. Key considerations during this phase include temperature degradation of the battery, charging practices, and the habits of EV users. From the standpoint of an EV manufacturer, producing a high-quality product is paramount. For EVs, this means ensuring that the lithium-ion battery, the vehicle's power source, has a long service life. Many aspects of the operational phase are directly related to maximizing this lifespan. Therefore, the following considerations will focus on how various factors can impact the longevity of lithium-ion batteries in EVs.

The first consideration is temperature degradation of the battery. EVs are used wherever consumers are, meaning that these batteries can be exposed to a wide range of environments depending on the user's location and the local climate. Seasonal variations pose a challenge to the longevity of lithium-ion batteries, as they may experience overheating in high temperatures or damage from exposure to low temperatures. This cycling of extreme temperatures can significantly reduce the battery's expected service life. Lithium-ion batteries perform best at moderate temperatures, typically when they are in a state of storage. For example, in EVs, the battery is at an ideal temperature when the vehicle is not in operation [39]. However, this is impractical, as the primary purpose of the vehicle is transportation, not storage.

The second consideration is the consumer's charging practices. EVs require regular charging, but the frequency and manner of charging can impact the degradation of lithium-ion batteries. A common charging routine among EV users is to fully charge the battery overnight, drive until the battery is nearly or completely depleted, and then repeat this cycle. This practice is harmful to lithium-ion batteries. Charging the battery for extended periods, such as overnight, can cause overheating, which contributes to battery degradation [40]. As mentioned previously, extreme temperature variations can negatively affect the battery's lifespan. To promote a healthier charging cycle, EV users should aim to maintain a 20% charge at all times and avoid charging beyond an additional 50% at any given time. This balanced approach helps mitigate the thermal stress on the battery and extends its operational life.

The third consideration in the operational life of a lithium-ion battery is the driving habits of the EV user. Just as charging practices can influence battery health, the manner in which the vehicle is driven also plays a significant role. Battery degradation can vary based on the user's routine driving patterns. For example, one user might commute to work five days a week, spending a significant amount of time on the highway at high speeds. In contrast, another user with a similar work schedule might have a shorter commute that only involves driving on smaller streets at lower speeds. These variations in driving conditions between users significantly impact the battery's lifespan [41]. The user with the longer, high-speed commute is likely to experience faster battery degradation, whereas the user with the shorter, lower-speed commute imposes less strain on the battery, resulting in a longer lifespan.

Overall, the operational stage has a significant impact on the service life of EV batteries. Factors such as environmental conditions, charging practices, and driving routines all influence battery longevity. By understanding and optimizing these factors, users can enhance the efficiency and extend the lifespan of their EV batteries.

2.3. End-of-Life Phase

Following the operational stage, the end-of-life phase is concerned with the final disposition of the EV's lithium-ion battery. Several options are available for battery disposal, including complete disposal, material recovery and reuse, or various recycling methods, which will be explored in detail later. However, each option comes with its own set of challenges, including potential inefficiencies and costs, which may impact the sustainability of the chosen method for the battery's end-of-life phase.

2.3.1. Challenges in Battery Disposal

Before selecting a disposal method, it is crucial to consider the inherent challenges associated with battery disposal. These challenges include additional costs, limited opportunities for secondary applications, and the competitive market for new batteries.

One significant challenge is the additional expense involved in partial recycling of battery components. Specifically, the valuable metals within batteries, such as lithium and cobalt, are highly sought after. However, the cost of extracting these metals from used batteries is often higher compared to sourcing them through traditional mining. This disparity arises because the process of recovering metals from spent batteries is more complex and resource-intensive than mining new materials. Another challenge is the limited potential for second-life applications of used batteries. Second-life applications involve repurposing a used battery for a different function, such as using an EV's battery to power industrial machinery. However, the chemical composition of lithium-ion batteries changes significantly over time, making it difficult to effectively repurpose them for new uses. The rapid growth in EV production has led to a competitive market for new batteries. As demand for new batteries increases, manufacturers compete by lowering prices to attract customers. This price competition reduces the incentive to seek out and reuse old batteries, making new batteries more attractive despite their lower cost [29].

2.3.2. Opportunities for Circular Practices

Despite the challenges associated with lithium-ion battery disposal, there are significant opportunities to integrate these batteries into a circular economy. The circular economic model envisions a cycle where end-of-life stages connect back to the beginning life stages, promoting sustainability and resource efficiency. While there are hurdles to effective disposal, they do not preclude the potential for reusing and recycling these batteries within a circular framework. Recycling methods, which will be discussed in detail in subsequent sections, offer a pathway to align with circular practices. Additionally, the EV industry is expanding rapidly, driven by increasing efforts to address climate change and enhance sustainability [42]. As the industry grows, so too will the regulatory frameworks designed to mitigate environmental impacts and promote the efficient disposal of EV batteries [43]. Government regulations and industry standards are likely to evolve, reducing the challenges associated with battery disposal and fostering more effective circular economy practices. Current strategies for integrating lithium-ion batteries into a circular economy are already in place and will be explored further in the following sections.

3. Circular Economy Strategies for End-of-Life EV Batteries

3.1. Battery Recycling Technologies

Battery recycling is crucial for sustainability, as it facilitates the recovery of valuable materials and reduces energy consumption. Recycling could potentially lower the primary demand by 25–64% between 2040 and 2050, according to projected demand figures. This suggests that waste streams might significantly contribute to meeting future raw material needs [44]. The battery recycling market is also projected to expand, with estimates suggesting that it could grow from USD 17.2 billion in 2021 to USD 23.2 billion by 2025, at a CAGR of 6.1%. This growth is fueled by the increasing adoption of EVs, stringent environmental regulations, and the rising value of recycled battery materials such as lithium, cobalt, and nickel [45]. In line with government policies that promote green initiatives, efforts such as those in Storey County, Nevada—where American Battery Technology Company (ABTC) has received over USD 70 million in U.S. DOE grants—are advancing the recycling and commercialization of battery metals to create a domestically-sourced circular supply chain [46]. Li-Cycle Corp., Toronto, ON, Canada, is a leading lithium-ion battery resource recovery company that operates several recycling facilities across North America, including Ontario, Canada. The company uses a proprietary hydrometallurgical process to recover up to 95% of all constituent materials found in lithium-ion batteries, including lithium, cobalt, and nickel. Li-Cycle's approach not only helps mitigate the environmental impact

associated with battery disposal but also ensures that valuable materials are efficiently reintroduced into the supply chain, supporting sustainability goals [47]. Northvolt, a Swedish battery manufacturer, is developing a comprehensive recycling program called Revolt, which focuses on recovering metals such as lithium, cobalt, and nickel from old EV batteries. Northvolt's recycling facility in Vasteras, Sweden, uses a combination of mechanical and hydrometallurgical processes to achieve high recovery rates for valuable battery materials. The company aims to produce batteries with up to 50% recycled material by 2030, aligning with broader sustainability and circular economy goals [48]. The battery recycling employs different methods such as pyrometallurgical, hydrometallurgical, bioleaching, and direct recycling processes to efficiently extract and repurpose materials for new battery production. A flow chart of the conventional treatment processes of spent Li-batteries (LIBs) is given in Figure 5.

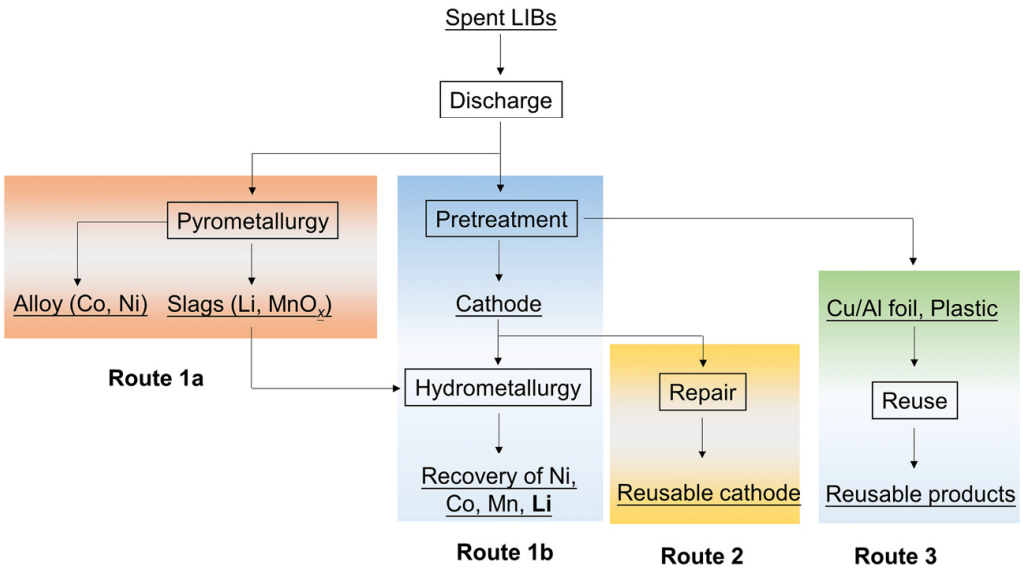


Figure 5. Conventional flow chart of treatment processes of spent LIBs (reproduced with permission from [49]).

Pyrometallurgical processes involve high-temperature smelting to recover valuable metals, while hydrometallurgical methods use aqueous solutions to leach out metals, offering lower energy consumption. Bioleaching utilizes microorganisms to extract metals from spent batteries, presenting a potentially eco-friendly alternative. Direct recycling aims to preserve battery materials' original structure, facilitating their reuse with minimal processing. Each method offers distinct advantages and limitations, and their combined use can optimize resource recovery and reduce environmental impact [50]. Table 1 provides a comparison of these recycling methods. These advanced technologies not only enhance the effectiveness of battery disposal but also contribute to the development of a more robust circular economy. By refining these recycling methods, we can improve resource recovery and reduce environmental impact, paving the way for more sustainable practices in battery management.

Table 1. Comparison of recycling methods [51–54].

Recycle Method	Highlights	Advantages	Disadvantages
Pyrometallurgical	• Involvement of high-temperature for smelting of batteries. • Frequently used for extraction of Co and Ni	• Simple process • High productivity • Industrial scale-capacity	• Requirement of high energy • Emission of hazardous gases • Limited number of materials reclaimed
Hydrometallurgical	• Involves the use of acids and reductants • Most of battery components are recovered as metals (Cu, Al) or salts (Li, Ni, Mn, etc.)	• Low energy consumption • Ease of operation • Low emission of toxic gases • Low cost • Higher energy efficiency	• Complexity in the selection of chemicals • Waste water management problem • Higher consumption of reagents
Bioleaching	• Microorganisms such as bacteria or archaea are used to extract metals.	• Environmentally competitive • Low cost • The addition of a proper catalyst can increase the rate of reaction and leaching yield	• Higher processing cost and environmental impact • Slow process kinetics • Susceptible to contamination
Direct recycling	• Preserves cathode morphology with minimal processing	• Low pollution • Low energy consumption • Less greenhouse gas emission	• Still needs time to develop and mature

3.1.1. Overview of Existing Recycling Methods

EV batteries comprise cells that include a cathode, anode, electrolyte, and separator, arranged in series or parallel configurations. These batteries typically have a lifespan of around 10 years; however, factors such as overcharging and excessive discharging can accelerate their degradation [39]. As EV batteries approach the end of their useful life, they are often discarded or replaced with newer models. Repurposing or reusing these batteries for alternative storage applications presents an opportunity to extract additional value. The growing demand for materials used in EV batteries highlights their significance. This increasing demand underscores the importance of efficient recycling methods to manage the supply and sustainability of these critical materials.

3.1.2. Innovations in Battery Recycling Technologies

The rapid evolution of EV battery technology has significantly impacted both the transportation and production sectors. Advances in charging capabilities and vehicle design have not only improved performance and affordability but have also enhanced the safety and efficiency of discharging and recycling EV batteries. Companies like Li-Cycle, Redwood Materials, and American Battery Technology Company are developing proprietary recycling technologies to maximize material recovery and reduce environmental impact [55]. Innovations in battery recycling technologies are influenced by several factors, including advancements in processing techniques, supply-chain stability, decarbonization efforts, and regulatory pressures and incentives [56]. Research-driven improvements in these areas are helping to ensure the quality and efficiency of battery recycling processes. These developments support the goal of making recycling more effective and economically viable, while also securing local raw materials at competitive prices. Innovations in battery recycling technologies are also addressing the challenge of handling emerging battery chemistries, such as solid-state and lithium–sulfur batteries, which require specialized recycling methods. Efforts are underway to develop scalable processes for these new types of batteries to ensure they can be efficiently recycled as their use becomes more widespread [57,58]. Furthermore, advancements in machine learning and artificial intelligence are being integrated into recycling systems to optimize sorting, identify materials with greater precision, and improve overall recovery rates [59]. These technological advancements not only enhance the effectiveness of recycling but also contribute to the long-term sustainability and economic viability of battery recycling initiatives.

3.2. Second-Life Applications

EV batteries have a finite lifespan, but their repurposing and reuse offer valuable opportunities for creating alternative energy solutions. For instance, these batteries are increasingly being utilized in solar panel systems to store energy for use when sunlight or wind is unavailable [60]. Additionally, they are being employed in electric fast-charging stations that store alternative energy, fostering innovation in transportation infrastructure. Although EV batteries contain harmful minerals, their recycling could act as a catalyst for improving the environmental practices of the mining industry [61]. This not only helps reduce the carbon footprint but also promotes the growth of renewable energy sources. A utilization chain of an EV battery throughout its lifecycle is shown in Figure 6.

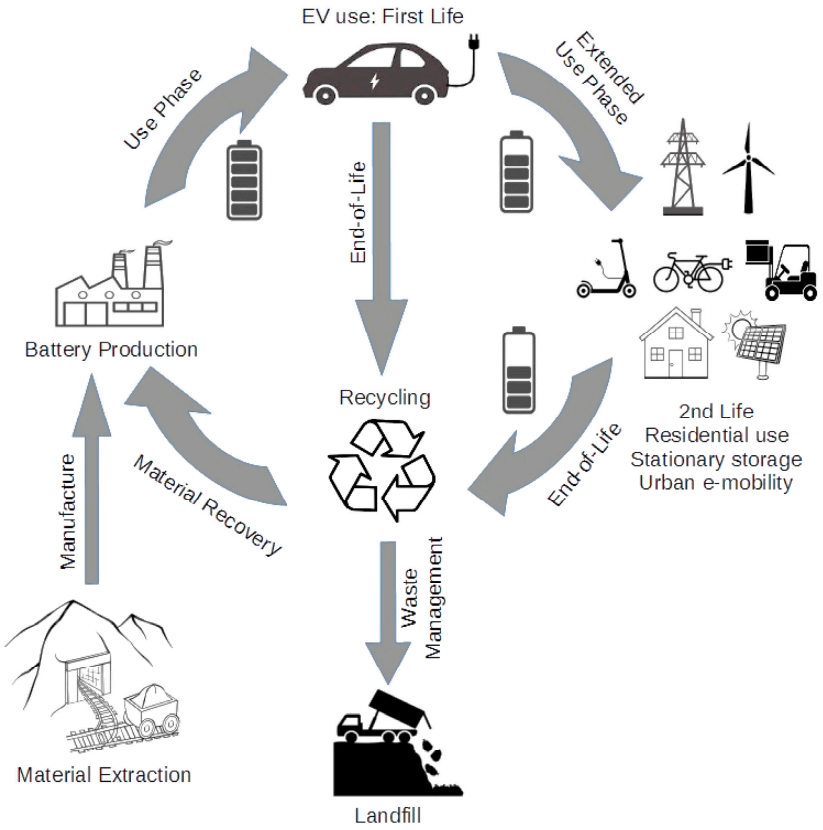


Figure 6. EV battery utilization chain throughout its lifecycle [62].

When an EV battery reaches the end of its life, there are several options for its management. One option is disposal, typically used when the battery is severely damaged or destroyed beyond repair, rendering it unsuitable for reuse. Another option is recycling, particularly valuable when the battery contains metals that can be recovered and repurposed for new applications. Additionally, reusing batteries can offer significant market value. Batteries with reduced capacity or remaining energy can be utilized in secondary applications that require lower energy levels [62]. As EV technology and battery storage continue to advance, the demand for raw materials for these second-life applications is growing, highlighting the importance of effective battery management. With the advancement of EV technology and battery storage solutions, innovations in battery diagnostics, predictive analytics, and automated processing are improving the management of end-of-life batteries. These developments enhance the accuracy of battery health assessments, increase recycling efficiency, and facilitate the adaptation of batteries for new applications. The growing demand for raw materials for second-life applications underscores the importance of effective and sustainable battery management strategies.

3.2.1. Reuse of EV Batteries for Stationary Energy Storage

Reusing and recycling EV batteries offers valuable opportunities to extend the life of newer batteries and support sustainability. Many EV batteries find a second life in stationary energy storage systems, such as power grids or backup power sources. These batteries can be repurposed for applications requiring lower energy levels or integrated into other energy storage systems [63]. Several companies disassemble old EV batteries, recover and recycle valuable components, and supply them to industries in need of these materials. Additionally, many independent companies are investing in recycling facilities, boosting the demand for cathode materials and increasing profitability. While battery recycling is not yet a critical issue, its importance is expected to grow significantly in the future as technology advances and secondary applications expand. For instance, companies like B2U are repurposing old EV batteries to create solar panels, which can maintain grid operations cleanly for over five years before being recycled into new batteries [64]. The recycling process for EV batteries typically involves four main steps. First, the batteries are collected and sorted based on their type and condition. Second, they are disassembled and discharged to safely remove any residual energy. Third, the batteries undergo pretreatment, which involves shredding them into smaller pieces to facilitate further processing. Finally, the materials are recovered using chemical processes [65,66]. To extract and purify the valuable materials, such as nickel, cobalt, and lithium-ion phosphate, different methods like pyrometallurgy, hydrometallurgy, and direct recycling methods are employed. Due to the complex nature of these materials, specialized techniques and equipment are required to effectively dismantle and process them [51].

3.2.2. Repurposing Batteries for Nonvehicular Applications

EV batteries, which convert and store chemical energy as electricity, inevitably experience degradation over time, leading to reduced capacity and performance. Factors such as temperature exposure and usage conditions can accelerate this degradation. When these batteries reach the end of their useful life, proper disposal is crucial to prevent environmental harm while maximizing societal benefits. While recycling is an option, it poses challenges, including potential contamination of wildlife and the high costs associated with extracting valuable materials like lithium, cobalt, and nickel through smelting. Repurposing offers a promising alternative to recycling. By finding new uses for degraded batteries, we can extend their value beyond vehicular applications. For example, Nissan has repurposed batteries to power streetlights in Japan, Renault has used them to back up elevators in Paris, and GM has employed repurposed Chevy Bolt batteries to support its data center in Michigan [67]. The Nissan Leaf Energy Storage Project is a notable example of repurposing end-of-life EV batteries for stationary energy storage. Launched in 2016 in collaboration with Eaton and a local utility, the project involves selecting and testing used batteries from Nissan Leaf vehicles based on their remaining capacity. These batteries are integrated into modular energy storage systems that are connected to the grid. The systems store excess renewable energy and provide backup power during peak demand, thus extending battery life and reducing waste while enhancing grid stability and supporting renewable energy integration [68]. BMW's Second-Life Battery Systems represent another successful approach to repurposing EV batteries. The company utilizes batteries from its i3 and i8 models to create energy storage solutions for commercial and residential use. These repurposed batteries store energy generated from solar panels and release it during high-demand periods, demonstrating how extending battery life can contribute to energy efficiency and support the adoption of renewable energy sources [69]. As EV battery technology evolves and cathode materials become more complex, repurposing and recycling processes may face increased difficulty, particularly with newer, heavier batteries. However, advancements in technology present opportunities to streamline these processes. By focusing on direct recycling and repurposing, costs can be minimized and handling techniques standardized, potentially improving regulatory practices and fostering innovative partnerships within the industry [65]. Despite the challenges, there are significant

opportunities for companies to develop technologies and strategies that enhance battery repurposing and recycling in the future.

3.3. Material Recovery and Resource Conservation

The transportation sector is undergoing a rapid transformation as automotive manufacturers shift from gas-powered vehicles to EVs. This shift has intensified the demand for key materials used in EV batteries, such as lithium, cobalt, and nickel, leading to significant advancements in extraction and processing technologies [70]. For instance, improvements in lithium retrieval methods have increased efficiency by over 80%, making the costs comparable to newly produced materials [21]. By the end of 2021, a total of at least nineteen critical materials recovery plants were set up across nine countries, including China, the United States, and Canada, with a combined capacity of around 322,500 tons annually [50]. As EV batteries approach the end of their lifecycle, the critical question arises: Should they be discarded, or can they be recycled? Proper disposal is essential to minimize environmental impact and maximize resource recovery. This is where Total Manufacturing Recovery (TMR) initiatives come into play [71]. A notable example is B2U, a company specializing in repurposing used EV battery components. B2U integrates these components into their solar panel systems, allowing them to store energy when sunlight is insufficient. When solar panels are not producing enough power, the repurposed batteries discharge energy back into the grid, functioning similarly to a generator [72]. This approach not only enhances the efficiency of renewable energy systems but also helps reduce the carbon footprint by providing a sustainable source of electricity for homes and businesses. By focusing on material recovery and resource conservation, companies like B2U are pioneering solutions that address the environmental challenges associated with EV battery disposal and contribute to a more sustainable energy future.

3.3.1. Recovery of Valuable Materials from Spent Batteries

Recovering valuable materials from spent batteries is crucial for environmental sustainability but presents several challenges. Spent batteries, once used in various settings such as households, offices, and schools, must be sorted and processed to extract reusable materials. The recovery process often begins with acid leaching, a technique that uses acids to dissolve metals and convert them into more soluble forms [73]. While this method is effective in extracting valuable metals, it can produce acid residues that may pose environmental risks. To address these challenges, both physical and chemical methods are employed. Physical methods, such as crushing and heating, facilitate the disassembly of battery components and increase the efficiency of recycling. Chemical methods, including hydrometallurgical and pyrometallurgical processes, are used to recover metals like lithium at high temperatures. These techniques enable the effective extraction of metals while minimizing environmental impact [74]. As demand for raw materials continues to rise, advancements in these recovery processes are essential to ensure sustainable management of battery waste and reduce the ecological footprint of battery disposal.

3.3.2. Strategies for Minimizing Waste and Environmental Impact

Processing plants that handle resources and raw minerals depend heavily on trucking for transportation and waste removal. This reliance results in significant pollution and substantial waste generation [50]. As populations grow and operational costs increase, the distances traveled by trucks lengthen, leading to higher CO_2 emissions and further environmental degradation [75]. Despite discussions about the potential for newer technologies to address these issues, tangible progress in reducing the environmental impact of trucking in the industry has been minimal.

Figure 7 illustrates the challenges associated with Environmental Policy Stringency (EPS) and its impact on adhering to environmental policies. While EPS is designed to address and mitigate pollution in various areas, including air quality and greenhouse gas emissions, it often has limited influence on the mining industry. Instead, these policies are

more focused on controlling broader environmental issues rather than directly regulating the specific practices of mining operations [76].

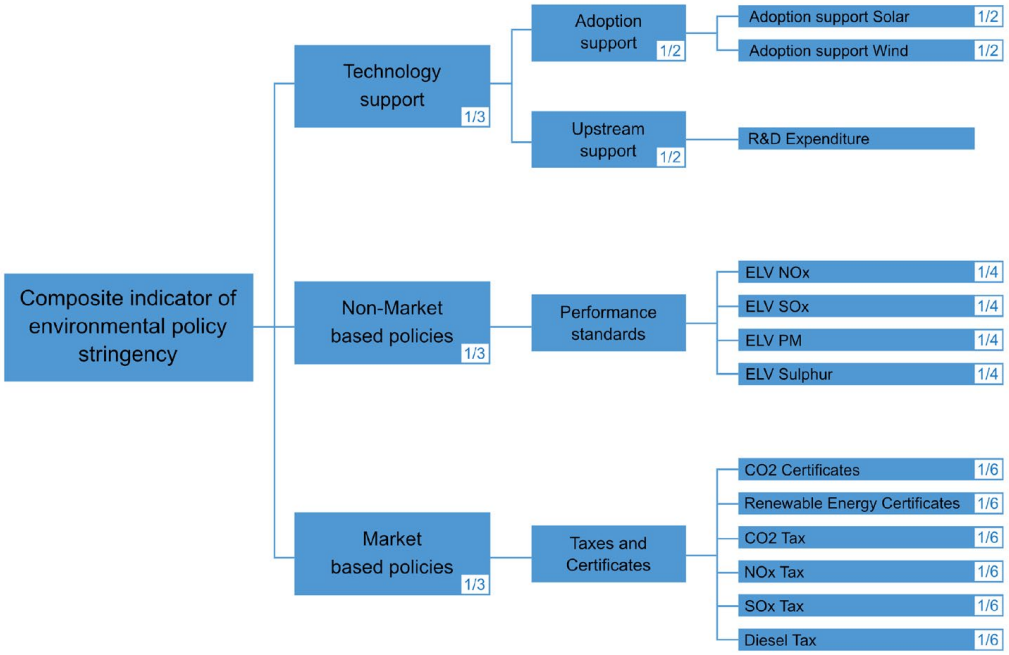


Figure 7. Environmental policy stringency (EPS) index showing advantages of environmental policies [76].

EV batteries have been shown to reduce gas consumption and waste, promoting cleaner and safer transportation. However, focusing solely on enhancing EV battery recycling without considering its environmental impact and energy lifespan could lead to significant consequences [77]. Effective long-distance travel requires a balance between reducing the carbon footprint of transport operations, minimizing fuel consumption, and transitioning to EVs. This shift results in increased distances for transporting raw minerals and materials [76]. While these changes contribute to energy efficiency and improved infrastructure, they also underscore the need for sustainable practices in both battery recycling and mineral transportation to ensure long-term environmental benefits.

4. Environmental and Social Impacts

4.1. Environmental Benefits of Circular EV Batteries

In a circular economy, the aim is not merely to recycle products at the end of their lifecycle but to extend the overall useful life of the products [78]. Although maintaining and repurposing these old products requires fresh raw materials, the environmental benefits of a circular economy are not solely derived from reducing raw material consumption. Instead, the primary advantage lies in decreasing the number of new EV batteries that need to be produced. This reduction results from a slower decline in the number of units in use, as these units are frequently refurbished or repurposed. Consequently, fewer batteries end up in landfills, and the cost of production decreases, leading to significant environmental and economic benefits.

4.1.1. Reduction in Environmental Pollution and Resource Depletion

The lithium industry significantly impacts the environment, from ecosystem destruction during mining to pollution during refinement, production, and disposal. Disposing of lithium batteries in landfills poses unique risks, including heavy metal contamination and the potential for fires [79]. A comprehensive cradle-to-grave lifecycle analysis by Bawankar et al. [80] utilized data from the Ecoinvent and BatPaC databases for NMC811 Lithium-Ion Batteries. They identified 15 areas where environmental impacts could occur, providing

insights into the total lifecycle environmental impact, normalized results, weighted results, and the environmental impact during the use stage. Their findings revealed that, while unnormalized data highlighted resource use in energy carriers, land use, and fossil fuels as the top contributors to environmental effects, the normalized and weighted data indicated fossil fuels, energy carriers, and ionizing radiation as the primary contributors. The study emphasized that these findings were heavily influenced by the energy sources of the electrical grid at the production site. Therefore, a significant way to reduce the environmental impact of lithium-ion batteries is to manufacture them using an electrical grid powered by renewable energy. Additionally, the authors noted the substantial water usage required by the lithium industry. This issue has been highlighted by The New York Times, which reported significant water use as a point of contention between the lithium industry, environmental activists, and indigenous groups [81].

4.1.2. Contribution to a Sustainable Materials Lifecycle

To understand how EV batteries can contribute to a sustainable economy, it is essential to first identify their composition. The materials within these batteries can be reused or recycled into various products, depending on their nature. A typical lithium-ion battery comprises four main components: a positive cathode made of lithium and other metals, an anode made of graphite, a barrier that separates the two while allowing electron flow, and an electrolytic solution [82]. However, it is important to note that chemical changes occur in these materials over the battery's lifespan, which contribute to the battery's eventual failure. As electrons travel between the anode and cathode, a solid electrolyte film begins to form on the anode [83]. To make the graphite useful again, it must also go through the recycling process. Understanding these chemical changes is crucial for recovering and repurposing these materials effectively. While knowing how to recover materials is one step, applying them to create new products in a manner that supports a sustainable lifecycle presents a different challenge. Identifying potential new products that can be made from each of the spent components is essential for advancing towards a circular economy. For example, the cathode, due to its valuable metal content, is often directly recycled into new cathodes. This process varies depending on the recycling method. An emerging technique, known as "cathode-to-cathode" recycling, is being employed on a small scale by certain companies. This method involves extracting the cathode first to preserve it before processing the rest of the battery [84]. The preserved cathode can then be incorporated into a new battery. However, the majority of cathode material is typically shredded along with the rest of the battery, mixing with the electrolytic solution and the anode to form a material industrially referred to as "black mass" [84]. The goal during further processing of this black mass is to extract individual metals, as discussed in Section 3.3. In addition to lithium, these metals can include nickel, cobalt, and manganese [85]. Each of these metals has applications beyond being turned back into cathodes. For instance, nickel can be used to plate other metals, making them corrosion-resistant or serving as catalysts for chemical reactions. It is also crucial in desalination plants when combined with copper into an alloy [86]. Similarly, cobalt has various uses outside of batteries, such as in the production of airbags, hard metals, and diamond tools. Like nickel, cobalt can also be used for corrosion resistance and as a catalyst for chemical reactions [87]. The spent graphite anode offers several recycling options. Traditionally, graphite is used in products like writing implements, solid lubricants, and nuclear core stabilizers, or converted into graphene [88]. It can also be recycled into new anodes for lithium-ion batteries. Innovative recycling methods have emerged, allowing spent anodes to be transformed into cathodes for dual-ion batteries [89]. This versatility makes graphite a highly sustainable material, given the various ways it can be processed and repurposed. In fact, the recycling process for graphite is very competitive with the production of new graphite [90]. Additionally, beyond its conventional uses, pencil lead can be synthesized into a graphite–silica composite anode that performs comparably to standard lithium-ion battery anodes [91].

4.2. Social Considerations and Stakeholder Engagement

In society, the pervasive attitude of consumerism needs to be addressed to reduce the demand for raw materials, production, and prevent losses in the recycling cycle. This requires decreasing consumer demand and promoting the longevity of functional technology. For instance, cellphones are typically replaced every 12 to 18 months [61]. Shockingly, as of 2022, less than 5% of lithium-ion batteries are recycled globally, according to a division of the American Chemical Society [92]. This section will explore the current state of community involvement in recycling, societal attitudes, and external factors that both aid and hinder public participation in recycling efforts.

4.2.1. Community Involvement in Circular Battery Initiatives

To effect meaningful change, the environmental impact of lithium-ion batteries requires action on multiple levels, especially in policy, which will become increasingly relevant in the coming years. However, significant steps can also be taken at the local and business levels. Companies like Apple and Samsung offer trade-ins for their devices, providing credit toward new purchases or ensuring responsible recycling of old devices. Encouraging consumers to make fewer frivolous phone purchases could significantly reduce the number of discarded lithium-ion batteries. While trade-in policies are a good start, they do not necessarily mobilize communities toward broader action. It is crucial for governments to disseminate easily accessible information about which products contain lithium-ion batteries and their detrimental environmental effects. Additionally, providing convenient recycling options is essential to encourage responsible disposal and recycling of these batteries.

To create effective recycling policies, the United States could look to successful examples from Europe and other regions. For instance, Germany enforces a deposit scheme for plastic bottles and cans: consumers pay a deposit when purchasing these items and receive a refund upon returning them to the vendor [93]. This system contrasts with the American approach, where financial compensation is provided at the point of recycling, creating an incentive rather than an economic obligation. Germany's approach effectively ensures a higher degree of participation in recycling, reflected in their leading global recycling rate of 69.1% as of 2022 [94]. In the United States, a significant issue is the contamination of recycling streams with nonrecyclable items—one in four items sent for recycling cannot be processed [95]. This discrepancy between public support for recycling and actual recycling behavior highlights the need for better public education and policy enforcement. Germany's deposit system effectively educates consumers about what can be recycled by associating deposits with recyclable items. Even if consumers cannot return their recyclable items, they are more likely to recognize that these items should be recycled and take appropriate action. The United States could also consider policies from other countries, such as South Korea's phase-out of single-use items like disposable cups [93]. This strategy increases recycling rates by reducing the total amount of recyclable material in circulation, thus improving the recycling percentage. These policy frameworks could be adapted to address the recycling of EV batteries, ensuring that valuable materials are recovered efficiently and environmental impacts are minimized.

4.2.2. Social Acceptance and Ethical Considerations in End-of-Life Practices

Current end-of-life practices for lithium-ion batteries are generally not socially accepted, despite strong public support for recycling. A qualitative survey conducted by the World Economic Forum found that 94% of Americans favor recycling, but only 35% actively participate due to a lack of convenient access [96]. This gap highlights the need for more public infrastructure to facilitate the recycling of waste, especially batteries, which require specialized processes. Many states with recycling initiatives have specific rules about what can and cannot be recycled, with processes in place to measure and manage the materials collected. An evaluation matrix by Ball Corporation identified Maine as having the best recycling performance in the United States, based on metrics for recycling cardboard boxes,

PET bottles, various metals, glasses, and general packaging [97]. However, this evaluation did not include electronics recycling, underscoring a critical area that needs attention. Electronics recycling remains largely inaccessible to the public. Given the ubiquity of electronic devices in modern life, it is essential to make electronics recycling equally pervasive. One potential solution is to implement dedicated electronic recycling dumpsters in neighborhoods, allowing residents to dispose of their electronics conveniently. These dumpsters could be serviced on a regular schedule, integrating electronic waste management into the routine waste collection system and significantly improving recycling rates for lithium-ion batteries and other electronic components.

Aside from social considerations, there are significant ethical improvements to the lithium lifecycle as unit recycling becomes more viable. Strip mining in the lithium industry consumes excessive amounts of water and land, often at the expense of native tribes. This has led to protests from environmental and indigenous advocacy groups against further land development projects for lithium mines, including acts of civil disobedience such as setting up encampments on planned development sites [81]. In addition to encroaching on native cultural lands and disturbing local wildlife, lithium mining can have severe impacts on farming and agriculture. There are concerns that the water usage required for lithium mining operations could negatively affect local farmers by diverting water away from their livestock and crops [98]. By increasing the recycling of lithium-ion batteries, the need for new lithium mining could be reduced, thereby lessening the environmental and social impacts associated with mining. Theoretically, if more recycled units are used in manufacturing, lithium-ion battery production could rely less on mining, reducing the overall output demands on new lithium extraction. This shift towards recycling could help mitigate the negative effects on indigenous lands, local ecosystems, and agricultural activities, promoting a more sustainable and ethical lifecycle for lithium batteries.

5. Challenges and Barriers

5.1. Technological Challenges

The concept of a circular economy is still emerging within the EV battery industry. While EVs have gained popularity only in recent years, strategies for managing EV batteries at the end of their lifecycle are even less developed. As the number of batteries approaching the end of their useful life increases, it becomes crucial to address these challenges now. By doing so, we can ensure that valuable materials are not wasted or improperly disposed of. Proactively developing and implementing effective recycling and reuse strategies will be essential for managing the growing volume of end-of-life batteries and advancing the sustainability of the industry.

5.1.1. Limitations in Current Recycling Technologies

As lithium battery technology evolves rapidly, keeping pace with recycling advancements becomes increasingly challenging [51]. The EV industry, still in its formative years, is undergoing frequent trials of new battery designs to determine the most effective solutions. Ongoing modifications aimed at enhancing battery efficiency and vehicle performance continually alter the materials used, complicating the recycling process. Perfecting recycling methods will be difficult until the industry stabilizes and a well-established standard for effective battery design emerges over time.

5.1.2. Technical Obstacles in Repurposing and Second-Life Applications

Repurposing lithium batteries for applications such as home energy storage, grid integration, or low-speed EVs presents significant technical challenges [99]. One major hurdle is assessing the state of health (SoH) of the battery, as different applications have varying regulatory standards and performance requirements. Currently, the technology for accurately evaluating SoH is not advanced enough to facilitate the timely and efficient repurposing of lithium batteries [100]. Advances in research and development are essential

to overcoming these obstacles and expanding the viable options for utilizing spent lithium batteries beyond their initial lifecycle.

5.2. Regulatory and Policy Challenges

Even with the ideal technology for recycling and repurposing batteries, its effectiveness would be limited without the appropriate regulations and policies to guide funding and define target applications. Given the rapid advancements in the industry, it is anticipated that growing interest will lead to more opportunities for refining these technologies and establishing the necessary frameworks to support their optimal use [50].

5.2.1. Evaluation of Existing Regulations and Policies

Currently, governmental legislation regarding battery recycling remains underdeveloped, reflecting the industry's relative novelty [56]. Among the major markets, China leads with stringent regulations, and it is projected to have recycled 2.312 million tons of spent lithium batteries by 2026 [101]. In contrast, the U.S. lags behind, with only 1% of spent lithium batteries currently being recycled [102]. Recent advancements, such as the Infrastructure Investment and Jobs Act of 2021, have initiated funding for battery recycling programs [103]. Given the rapid growth of the industry, it is anticipated that new regulations and policies will emerge in the coming years to address technological advancements and ensure effective recycling practices, provided continued investment and development in this area.

5.2.2. Recommendations for Policy Improvements to Support Circular Practices

To establish a circular economy for lithium batteries, increased funding and support for battery recycling technologies are crucial. In the U.S., both national and local efforts must be intensified. Although some legislation related to battery recycling has been enacted, these measures need to be expanded to unlock the full economic potential of this burgeoning industry [104]. Enhanced funding and robust regulations would encourage more companies to innovate and develop safer, more sustainable recycling technologies, driving significant advancements in the sector.

6. Future Directions and Research Needs

6.1. Research Gaps and Opportunities

6.1.1. Areas Requiring Further Investigation and Development

Recycling presents a significant challenge in establishing a circular economy for EV batteries. For a truly circular economy, effective recycling is essential. The concept involves not only reusing old batteries to create new ones but also repurposing them for less demanding applications, such as energy storage in solar power systems, which can extend their operational life [105]. Achieving a nearly perfect cycle of resource use hinges on overcoming current recycling hurdles. One major obstacle in recycling EV batteries is the complexity of their disassembly. EV batteries are highly intricate and packed with a variety of cells arranged differently by vehicle brand and model. This complexity, combined with the diverse materials used in each battery type, makes disassembly and material extraction challenging. The urgent need is for new technology or solutions that address the challenge of separate extraction processes for various elements [106]. Batteries are often assembled with various methods such as adhesive bonding, welding, and other connectors, which complicates the separation of materials. Additionally, battery degradation over time affects recyclability by altering the battery's form, which can pose health risks to those handling the recycling process [107]. This degradation contributes to the uncertainty in the recycling process, making it difficult to develop effective recycling solutions.

6.1.2. Potential for Interdisciplinary Collaboration and Knowledge Transfer

In the business world, battery knowledge is often closely guarded to maintain competitive advantage. While this secrecy serves business interests, it poses challenges for the engineering community, which relies on detailed data to understand battery lifecycles and improve technologies. Access to comprehensive battery information could lead to significant advancements in several areas. For instance, tracking the state of a battery throughout its life could enable the development of preventative maintenance measures. Additionally, understanding the battery's condition at the end of its life would facilitate the creation of more sophisticated disassembly robots. An example is the robot Daisy, which uses −176 °F freezing air to detach batteries from iPhone bodies [107]. To enhance recycling and battery technology, there needs to be greater knowledge sharing among companies. Tesla, for example, has embraced the open-source movement to advance EV technology, making valuable insights publicly available [108]. Embracing similar collaborative approaches, including integrating robotics and AI, could lead to more efficient and effective battery management and recycling solutions.

6.2. Roadmap for Future Circular EV Battery Initiatives

6.2.1. Key Steps toward Widespread Adoption of Circular Practices

The discussion of circular practices for EV batteries encompasses two key aspects: the technology enabling these practices and the businesses or policies that support them. In Europe, for instance, the concept of European Conformity (CE) embodies a comprehensive approach to circularity. CE involves both forward processes—such as production, material use, assembly, distribution, and consumption—and reverse processes—like repair, reconditioning, remanufacturing, recycling, and disposal [44]. This system evaluates products at the end of their lifecycle to determine which circular practices they qualify for, ensuring that materials are effectively managed and reused. However, the effectiveness of these circular practices is also heavily dependent on the technology available. Advanced technologies are crucial for efficient recycling and repurposing, and without them, the potential benefits of circular practices may be limited. Thus, while policies like CE play a vital role in promoting circularity, they must be supported by technological advancements to fully realize their potential.

6.2.2. Collaborative Efforts and Partnerships for Industry Transformation

From a business standpoint, maintaining secrecy and competitiveness is often seen as a strategic advantage. However, this approach can hinder the advancement of a circular economy for EV batteries. Managers and executives within the EV battery sector should consider adopting circular business models (CBMs) as an innovative means to extend product lifecycles and unlock new value propositions. Such models could foster cross-company and sector-wide collaborations, which are crucial for advancing recycling and repurposing technologies [109]. Recycling technology must be highly sophisticated to efficiently extract all valuable materials from EV batteries. Developing unique recycling processes for each individual EV design is impractical. Instead, focusing on creating a few versatile recycling processes for common battery designs would be more efficient and cost-effective. Some organizations are already pioneering this approach. For instance, South Korea has initiated a groundbreaking public-private partnership to establish a sustainable EV battery ecosystem through a memorandum of understanding (MOU) [110]. Such collaborations demonstrate the potential economic benefits of forming a circular economy. Research indicates that partnerships between manufacturers and retailers can achieve higher collection rates and overall welfare benefits [111].

This study highlights that willing collaboration, rather than stringent policies, is more effective in promoting recycling while minimizing adverse effects on welfare.

6.3. Trends towards a Circular Economy

6.3.1. Future Scientific Breakthroughs in EV Battery Recycling

There are numerous untapped breakthroughs in EV battery recycling that remain unexplored. While various methods are being investigated, the effects of thermal treatment in an oxidative atmosphere on the microstructure and composition of cathode and anode materials remain largely unstudied [112]. As noted, degradation of batteries can produce harmful substances, but promising advancements are on the horizon. Recent developments offer hope: new recycling processes are being researched that do not require the use of expensive or harmful chemicals [113]. Previously, battery recycling was considered hazardous due to the use of toxic chemicals, but this perception is shifting with these innovations. As the industry evolves, particularly with the growing prominence of EVs over internal combustion engines, a diverse range of facilities, capabilities, and approaches will emerge as more companies enter the battery recycling space [114]. Given the rapid pace of technological innovation, the transition from ICE to EVs holds significant potential for establishing a sustainable circular economy for EV batteries.

6.3.2. Increased Interest in EV Battery Research

In an era of rapid technological advancement, it is crucial to keep the future in focus. Developing a circular economy for EV batteries involves two main aspects: engineering innovations and incentive structures. Research into EV technology is supported by various sources, including government grants (e.g., National Science Foundation, National Institutes of Health), corporate R&D, and nonprofit foundations [115]. While these stakeholders are invested in research, their motivations can vary significantly. A key challenge to achieving a circular economy is overcoming planned obsolescence—the practice where products are intentionally designed to have a limited lifespan, encouraging repeat purchases. Addressing this issue is crucial for promoting recycling. The EV battery recycling market is projected to reach USD 15.8 billion by 2030, growing at a compound annual growth rate (CAGR) of 32.1% from 2023 to 2030 [116]. This indicates that a circular economy is not only feasible but also economically promising. However, obstacles like corporate greed can impede progress. For instance, a study suggests that if consumer demand were strong enough, EV manufacturers would recycle all batteries without additional incentives [117]. Despite this, EVs face social challenges, including skepticism about their environmental benefits and perceptions of their "coolness". If consumer pressure alone is not enough to drive a circular economy, government intervention becomes essential. Policies must be enacted to encourage collaboration and innovation in recycling. Suggested strategies include increasing funding for both incremental innovations and breakthroughs in recycling technology, supporting pilot projects that foster collaboration across the recycling value chain, and implementing market-pull measures to create a favorable economic and regulatory environment for large-scale EV battery recycling [27]. By aligning private sector interests with regulatory measures, we can foster a thriving, sustainable recycling ecosystem in this rapidly evolving technological landscape.

7. Conclusions

This review has explored various facets of the EV battery lifecycle, with a particular focus on achieving a circular economy. The crucial factor in this effort is managing the product's end-of-life effectively. Implementing processes that enable the recycling or repurposing of all EV batteries once they are no longer usable is essential for closing the loop of a circular economy. Such practices would not only reduce costs and enhance efficiency but also significantly improve environmental and societal outcomes. Despite the current challenges in scaling these processes, it is evident that the future holds promising advancements. As the demand for EV batteries grows, technological innovations will likely address these emerging issues. With ongoing research and development, the solutions needed to establish a robust circular economy for EV batteries are within reach.

The lifecycle of an EV battery remains a significant unknown, which contributes to consumer skepticism about purchasing EVs. One of the primary obstacles facing the EV industry is the limited transparency regarding battery lifespan. Addressing this issue requires both corporate initiatives and government regulations to drive meaningful change. For example, Cox Automotive's ALFRED system and health score aim to enhance transparency and build consumer confidence in EV transactions, akin to the trusted vehicle valuations provided by Kelley Blue Book for nearly a century [118]. While battery health is a critical concern for consumers, particularly those increasingly focused on environmental issues, there is also a demand for broader information beyond just battery life. To address this, the Global Battery Alliance (GBA) has introduced a novel approach to increase transparency. Their "battery passport" functions as a digital twin of the physical battery, capturing and storing vital information—such as provenance, composition, material flows, and manufacturing history—in a QR code [119]. This concept of maintaining a comprehensive record throughout a product's lifecycle could revolutionize how we manage and perceive product histories. Although the initial focus on batteries may seem niche, the principles of this approach have the potential to drive significant changes across various industries and even influence broader economic behaviors. The rise of EVs is undeniable, but achieving a full transition from internal combustion engines (ICEs) to EVs requires substantial effort and ambition. As stated, "Making the 2020s the decade of transition to EVs requires more ambition and action among both market leaders and followers" [120]. While EVs are gaining traction, they are not yet dominating the market. They remain more expensive than ICE vehicles, and their environmental benefits are somewhat tempered by the current state of power grids. This transition is a complex and labor-intensive process. Replacing the established ICE infrastructure with a clean, efficient EV ecosystem demands comprehensive changes, including local community preparations for this shift. For example, in Michigan, state and local leaders are actively preparing for the growth of EV and battery production facilities by creating programs to equip the workforce with necessary skills [121]. Just a few decades ago, the concept of EVs was virtually nonexistent in the minds of most consumers and workers. The rapid development of the EV industry aims to replace the ICE sector in a relatively short time, but the pace of this transition is slower than many would like, given the environmental urgency. President Biden's goal of achieving a 50% market share for EVs in the U.S. by 2030 underscores the high level of commitment needed [122]. While many countries have committed to this transition, the path to a circular economy for EV batteries is still in its early stages. Progress is being made at various levels, and while significant work remains, there is a clear and accelerating momentum towards a more sustainable future.

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References

1. Herrmann, F.; Rothfuss, F. Introduction to Hybrid Electric Vehicles, Battery Electric Vehicles, and off-Road Electric Vehicles. In *Advances in Battery Technologies for Electric Vehicles*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 3–16.
2. Electric Vehicles. Available online: https://www.iea.org/energy-system/transport/electric-vehicles (accessed on 30 August 2024).
3. Trends in the Electric Vehicle Industry—Global EV Outlook 2024—Analysis. Available online: https://www.iea.org/reports/global-ev-outlook-2024/trends-in-the-electric-vehicle-industry (accessed on 6 August 2024).
4. Electric Vehicles—Worldwide | Statista Market Forecast. Available online: https://www.statista.com/outlook/mmo/electric-vehicles/worldwide (accessed on 10 August 2024).
5. What Are the Consumer and Societal Reactions towards Electric Vehicles? Available online: https://www.greenbook.org/insights/what-are-consumer-reactions-to-electric-vehicles (accessed on 6 August 2024).
6. Ibrahim, A.; Jiang, F. The Electric Vehicle Energy Management: An Overview of the Energy System and Related Modeling and Simulation. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111049. [CrossRef]
7. Zhang, X.; Liang, Y.; Yu, E.; Rao, R.; Xie, J. Review of Electric Vehicle Policies in China: Content Summary and Effect Analysis. *Renew. Sustain. Energy Rev.* **2017**, *70*, 698–714. [CrossRef]

8. Mohammadzadeh, N.; Zegordi, S.H.; Kashan, A.H.; Nikbakhsh, E. Optimal Government Policy-Making for the Electric Vehicle Adoption Using the Total Cost of Ownership under the Budget Constraint. *Sustain. Prod. Consum.* **2022**, *33*, 477–507. [CrossRef]
9. Ralls, A.M.; Leong, K.; Clayton, J.; Fuelling, P.; Mercer, C.; Navarro, V.; Menezes, P.L. The Role of Lithium-Ion Batteries in the Growing Trend of Electric Vehicles. *Materials* **2023**, *16*, 6063. [CrossRef]
10. Das, U.K.; Shrivastava, P.; Tey, K.S.; Idris, M.Y.I.B.; Mekhilef, S.; Jamei, E.; Seyedmahmoudian, M.; Stojcevski, A. Advancement of Lithium-Ion Battery Cells Voltage Equalization Techniques: A Review. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110227. [CrossRef]
11. How Do Electric Cars Work? An In-Depth Guide. Available online: https://www.edmunds.com/electric-car/articles/how-do-electric-cars-work.html (accessed on 6 August 2024).
12. Batteries Are a Key Part of the Energy Transition. Here's Why. Available online: https://www.weforum.org/agenda/2021/09/batteries-lithium-ion-energy-storage-circular-economy/ (accessed on 6 August 2024).
13. Morse, I. A Dead Battery Dilemma. Available online: https://www.sciencemagazinedigital.org/sciencemagazine/21_may_2021/MobilePagedArticle.action?articleId=1692939 (accessed on 6 August 2024).
14. Woollacott, E. Electric Cars: What Will Happen to All the Dead Batteries? *BBC News*, 27 April 2021.
15. Inc, C. Cyient | Blogs | Shyam Sundar Pal. Available online: https://www.cyient.com/blog/author/shyam-sundar-pal (accessed on 6 August 2024).
16. EV Manufacturers Looking to Decarbonize—And Profit from It | HERE. Available online: https://www.here.com/learn/blog/ev-battery-sustainability-recycling (accessed on 6 August 2024).
17. What Is the Circular Economy, and Why Does It Matter That It's Shrinking? Available online: https://www.weforum.org/agenda/2022/06/what-is-the-circular-economy/ (accessed on 6 August 2024).
18. Pereira, P.M.; Vieira, C.S. A Literature Review on the Use of Recycled Construction and Demolition Materials in Unbound Pavement Applications. *Sustainability* **2022**, *14*, 13918. [CrossRef]
19. Bhutada, G. The Key Minerals in an EV Battery. Available online: https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/ (accessed on 10 August 2024).
20. Policy Challenges for Accessing Critical Minerals to Electrify Vehicle Transport. Available online: https://www.rff.org/publications/reports/policy-challenges-for-accessing-critical-minerals-for-electric-vehicles/ (accessed on 10 August 2024).
21. Battery Recycling: 10 Breakthrough Technologies. 2023. Available online: https://www.technologyreview.com/2023/01/09/1064886/battery-recycling-10-breakthrough-technologies-2023/ (accessed on 6 August 2024).
22. Alternative Fuels Data Center: Batteries for Electric Vehicles. Available online: https://afdc.energy.gov/vehicles/electric-batteries (accessed on 6 August 2024).
23. Zhang, R.; Fujimori, S. The Role of Transport Electrification in Global Climate Change Mitigation Scenarios. *Environ. Res. Lett.* **2020**, *15*, 034019. [CrossRef]
24. Zubi, G.; Dufo-López, R.; Carvalho, M.; Pasaoglu, G. The Lithium-Ion Battery: State of the Art and Future Perspectives. *Renew. Sustain. Energy Rev.* **2018**, *89*, 292–308. [CrossRef]
25. How Lithium-Ion Batteries Work. Available online: https://www.energy.gov/energysaver/articles/how-lithium-ion-batteries-work (accessed on 6 August 2024).
26. Thi, M.T.; Kim, C.; Kwon, S.; Kang, H.; Ko, J.M.; Kim, J.; Choi, W. Investigation of the Properties of Anode Electrodes for Lithium–Ion Batteries Manufactured Using Cu, and Si-Coated Carbon Nanowall Materials. *Energies* **2023**, *16*, 1935. [CrossRef]
27. Beaudet, A.; Larouche, F.; Amouzegar, K.; Bouchard, P.; Zaghib, K. Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials. *Sustainability* **2020**, *12*, 5837. [CrossRef]
28. Larouche, F.; Tedjar, F.; Amouzegar, K.; Houlachi, G.; Bouchard, P.; Demopoulos, G.P.; Zaghib, K. Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. *Materials* **2020**, *13*, 801. [CrossRef] [PubMed]
29. Deng, J.; Bae, C.; Denlinger, A.; Miller, T. Electric Vehicles Batteries: Requirements and Challenges. *Joule* **2020**, *4*, 511–515. [CrossRef]
30. Yu, D.; Huang, Z.; Makuza, B.; Guo, X.; Tian, Q. Pretreatment Options for the Recycling of Spent Lithium-Ion Batteries: A Comprehensive Review. *Miner. Eng.* **2021**, *173*, 107218. [CrossRef]
31. Liu, Y.; Zhang, R.; Wang, J.; Wang, Y. Current and Future Lithium-Ion Battery Manufacturing. *iScience* **2021**, *24*, 102332. [CrossRef]
32. Konda, K.; Moodakare, S.B.; Kumar, P.L.; Battabyal, M.; Seth, J.R.; Juvekar, V.A.; Gopalan, R. Comprehensive Effort on Electrode Slurry Preparation for Better Electrochemical Performance of $LiFePO_4$ Battery. *J. Power Sources* **2020**, *480*, 228837. [CrossRef]
33. Jiao, X.; Kirianova, A.V.; Xu, X.; Kapitanova, O.O.; Krivchenko, V.A.; Napolskiy, F.S.; Volkov, V.S.; Gallyamov, M.O.; Liu, Y. Conductive Additives for Improving the Rate Capability of Cathode Materials in Secondary Lithium Batteries. *ACS Appl. Energy Mater.* **2023**, *6*, 2855–2862. [CrossRef]
34. Lithium-Ion Batteries and Fluoromaterials | Fluorochemicals | Daikin Global. Available online: https://www.daikinchemicals.com/magazine/column-lithium-ion-battery-vol1.html (accessed on 6 August 2024).
35. Luchkin, S.Y.; Kirsanova, M.A.; Aksyonov, D.A.; Lipovskikh, S.A.; Nikitina, V.A.; Abakumov, A.M.; Stevenson, K.J. Cycling-Driven Electrochemical Activation of Li-Rich NMC Positive Electrodes for Li-Ion Batteries. *ACS Appl. Energy Mater.* **2022**, *5*, 7758–7769. [CrossRef]
36. Lai, X.; Chen, Q.; Tang, X.; Zhou, Y.; Gao, F.; Guo, Y.; Bhagat, R.; Zheng, Y. Critical Review of Life Cycle Assessment of Lithium-Ion Batteries for Electric Vehicles: A Lifespan Perspective. *eTransportation* **2022**, *12*, 100169. [CrossRef]

37. Khan, I.; Hou, F.; Le, H.P. The Impact of Natural Resources, Energy Consumption, and Population Growth on Environmental Quality: Fresh Evidence from the United States of America. *Sci. Total Environ.* **2021**, *754*, 142222. [CrossRef]
38. Yuan, C.; Cao, H.; Shen, K.; Deng, Y.; Zeng, D.; Dong, Y.; Hauschild, M. Water-Based Manufacturing of Lithium Ion Battery for Life Cycle Impact Mitigation. *CIRP Ann.* **2021**, *70*, 25–28. [CrossRef]
39. Han, X.; Lu, L.; Zheng, Y.; Feng, X.; Li, Z.; Li, J.; Ouyang, M. A Review on the Key Issues of the Lithium Ion Battery Degradation among the Whole Life Cycle. *eTransportation* **2019**, *1*, 100005. [CrossRef]
40. Liu, K.; Hu, X.; Yang, Z.; Xie, Y.; Feng, S. Lithium-Ion Battery Charging Management Considering Economic Costs of Electrical Energy Loss and Battery Degradation. *Energy Convers. Manag.* **2019**, *195*, 167–179. [CrossRef]
41. Guo, J.; Li, Y.; Pedersen, K.; Stroe, D.-I. Lithium-Ion Battery Operation, Degradation, and Aging Mechanism in Electric Vehicles: An Overview. *Energies* **2021**, *14*, 5220. [CrossRef]
42. Requia, W.J.; Mohamed, M.; Higgins, C.D.; Arain, A.; Ferguson, M. How Clean Are Electric Vehicles? Evidence-Based Review of the Effects of Electric Mobility on Air Pollutants, Greenhouse Gas Emissions and Human Health. *Atmos. Environ.* **2018**, *185*, 64–77. [CrossRef]
43. 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. Manage.* **2020**, *264*, 110500. [CrossRef]
44. Nurdiawati, A.; Agrawal, T.K. Creating a Circular EV Battery Value Chain: End-of-Life Strategies and Future Perspective. *Resour. Conserv. Recycl.* **2022**, *185*, 106484. [CrossRef]
45. MarketsandMarkets Battery Recycling Market Worth $23.2 Billion by 2025—Exclusive Report by MarketsandMarketsTM. Available online: https://www.prnewswire.com/news-releases/battery-recycling-market-worth-23-2-billion-by-2025--exclusive-report-by-marketsandmarkets-301051786.html (accessed on 29 August 2024).
46. Company, A.B.T. American Battery Technology Company Receives Contract for $57M Grant from US DOE for Construction of Commercial-Scale Lithium Hydroxide Refinery. Available online: https://www.prnewswire.com/news-releases/american-battery-technology-company-receives-contract-for-57m-grant-from-us-doe-for-construction-of-commercial-scale-lithium-hydroxide-refinery-301919344.html (accessed on 29 August 2024).
47. Krishnasamy, R. Li-Cycle Leads the Recycling of Lithium-Ion Batteries with High Resource Recovery Technology. Available online: https://techblitz.com/li-cycle/ (accessed on 29 August 2024).
48. Revolt: Closing the Loop on Batteries. Available online: https://northvolt.com/articles/revolt/ (accessed on 29 August 2024).
49. Liu, C.; Lin, J.; Cao, H.; Zhang, Y.; Sun, Z. Recycling of Spent Lithium-Ion Batteries in View of Lithium Recovery: A Critical Review. *J. Clean. Prod.* **2019**, *228*, 801–813. [CrossRef]
50. Baum, Z.J.; Bird, R.E.; Yu, X.; Ma, J. Lithium-Ion Battery Recycling—Overview of Techniques and Trends. *ACS Energy Lett.* **2022**, *7*, 712–719. [CrossRef]
51. 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]
52. Alipanah, M.; Reed, D.; Thompson, V.; Fujita, Y.; Jin, H. Sustainable Bioleaching of Lithium-Ion Batteries for Critical Materials Recovery. *J. Clean. Prod.* **2023**, *382*, 135274. [CrossRef]
53. Hua, Y.; Zhou, S.; Huang, Y.; Liu, X.; Ling, H.; Zhou, X.; Zhang, C.; Yang, S. Sustainable Value Chain of Retired Lithium-Ion Batteries for Electric Vehicles. *J. Power Sources* **2020**, *478*, 228753. [CrossRef]
54. Tanong, K.; Coudert, L.; Mercier, G.; Blais, J.-F. Recovery of Metals from a Mixture of Various Spent Batteries by a Hydrometallurgical Process. *J. Environ. Manag.* **2016**, *181*, 95–107. [CrossRef] [PubMed]
55. The World Is Powered by Batteries, but Who Is Leading the Charge in Battery Recycling? | Nasdaq. Available online: https://www.nasdaq.com/press-release/the-world-is-powered-by-batteries-but-who-is-leading-the-charge-in-battery-recycling (accessed on 29 August 2024).
56. 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]
57. Ahuis, M.; Doose, S.; Vogt, D.; Michalowski, P.; Zellmer, S.; Kwade, A. Recycling of Solid-State Batteries. *Nat. Energy* **2024**, *9*, 373–385. [CrossRef]
58. Wang, H.; Cao, X.; Liu, W.; Sun, X. Research Progress of the Solid State Lithium-Sulfur Batteries. *Front. Energy Res.* **2019**, *7*, 112. [CrossRef]
59. Pregowska, A.; Osial, M.; Urbańska, W. The Application of Artificial Intelligence in the Effective Battery Life Cycle in the Closed Circular Economy Model—A Perspective. *Recycling* **2022**, *7*, 81. [CrossRef]
60. Hua, Y.; Liu, X.; Zhou, S.; Huang, Y.; Ling, H.; Yang, S. Toward Sustainable Reuse of Retired Lithium-Ion Batteries from Electric Vehicles. *Resour. Conserv. Recycl.* **2021**, *168*, 105249. [CrossRef]
61. Costa, C.M.; Barbosa, J.C.; Gonçalves, R.; Castro, H.; Campo, F.J.D.; Lanceros-Méndez, S. Recycling and Environmental Issues of Lithium-Ion Batteries: Advances, Challenges and Opportunities. *Energy Storage Mater.* **2021**, *37*, 433–465. [CrossRef]
62. 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]
63. 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]

64. Olsson, L.; Fallahi, S.; Schnurr, M.; Diener, D.; Van Loon, P. Circular Business Models for Extended EV Battery Life. *Batteries* **2018**, *4*, 57. [CrossRef]
65. Striking Gold with EV Battery Recycling. Available online: https://www.bcg.com/publications/2023/striking-gold-with-ev-battery-recycling (accessed on 7 August 2024).
66. Sommerville, R.; Shaw-Stewart, J.; Goodship, V.; Rowson, N.; Kendrick, E. A Review of Physical Processes Used in the Safe Recycling of Lithium Ion Batteries. *Sustain. Mater. Technol.* **2020**, *25*, e00197. [CrossRef]
67. Overview of EV Batteries | GreenCars. Available online: https://www.greencars.com/greencars-101/overview-of-ev-batteries (accessed on 7 August 2024).
68. Nissan Partners with Enel to Launch Innovative "Second Life" Storage System for Used Electric Car Batteries. Available online: http://europe.nissannews.com/en-GB/releases/nissan-partners-with-enel-to-launch-innovative-second-life-storage-system-for-used-electric-car-batteries (accessed on 29 August 2024).
69. BMW Group UK Second-Life Battery Solution in Partnership with off Grid Energy. Available online: https://www.press.bmwgroup.com/united-kingdom/article/detail/T0318650EN_GB/bmw-group-uk-second-life-battery-solution-in-partnership-with-off-grid-energy?language=en_GB (accessed on 29 August 2024).
70. Mining for Electric Car Batteries: What You Need to Know. Available online: https://www.capitalone.com/cars/learn/finding-the-right-car/mining-for-electric-car-batteries-what-you-need-to-know/2395 (accessed on 7 August 2024).
71. Potts, E. Total Material Recovery: State-of-the-Art Battery Recycling for the EV Supply Chain. *Innovation News Network*, 23 November 2023.
72. Your Depleted EV Battery Pack Could Power the Grid after Sunset. Available online: https://www.autoweek.com/news/technology/a43937159/b2u-company-reusing-ev-battery-packs-to-store-solar-energy/ (accessed on 7 August 2024).
73. Tawonezvi, T.; Nomnqa, M.; Petrik, L.; Bladergroen, B.J. Recovery and Recycling of Valuable Metals from Spent Lithium-Ion Batteries: A Comprehensive Review and Analysis. *Energies* **2023**, *16*, 1365. [CrossRef]
74. Yun, L.; Linh, D.; Shui, L.; Peng, X.; Garg, A.; LE, M.L.P.; Asghari, S.; Sandoval, J. Metallurgical and Mechanical Methods for Recycling of Lithium-Ion Battery Pack for Electric Vehicles. *Resour. Conserv. Recycl.* **2018**, *136*, 198–208. [CrossRef]
75. Pulling The Weight of Heavy Truck Decarbonization. Available online: https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/ (accessed on 7 August 2024).
76. Mihai, D.M.; Doran, M.D.; Puiu, S.; Doran, N.M.; Jianu, E.; Cojocaru, T.M. Managing Environmental Policy Stringency to Ensure Sustainable Development in OECD Countries. *Sustainability* **2023**, *15*, 15427. [CrossRef]
77. Picatoste, A.; Justel, D.; Mendoza, J.M.F. Circularity and Life Cycle Environmental Impact Assessment of Batteries for Electric Vehicles: Industrial Challenges, Best Practices and Research Guidelines. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112941. [CrossRef]
78. Yang, Y.; Okonkwo, E.G.; Huang, G.; Xu, S.; Sun, W.; He, Y. On the Sustainability of Lithium Ion Battery Industry—A Review and Perspective. *Energy Storage Mater.* **2021**, *36*, 186–212. [CrossRef]
79. Heelan, J.; Gratz, E.; Zheng, Z.; Wang, Q.; Chen, M.; Apelian, D.; Wang, Y. Current and Prospective Li-Ion Battery Recycling and Recovery Processes. *JOM* **2016**, *68*, 2632–2638. [CrossRef]
80. Bawankar, S.; Dwivedi, G.; Nanda, I.; Macedo, V.D.J.; Kesharvani, S.; Meshram, K.; Jain, S.; Mishra, S.; Singh, V.P.; Verma, P. Environmental Impact Assessment of Lithium Ion Battery Employing Cradle to Grave. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103530. [CrossRef]
81. Ethics, Politics and Lithium Mining: In Conversation with Zayn Kaylan of Infinity Stone. Available online: https://mine.nridigital.com/mine_may23/lithium_ethics_infinity_stone (accessed on 10 August 2024).
82. Mekonnen, Y.; Sundararajan, A.; Sarwat, A.I. A Review of Cathode and Anode Materials for Lithium-Ion Batteries. In Proceedings of the SoutheastCon, Norfolk, VA, USA, 30 March–3 April 2016; pp. 1–6.
83. BU-808b: What Causes Li-Ion to Die? Available online: https://batteryuniversity.com/article/bu-808b-what-causes-li-ion-to-die (accessed on 7 August 2024).
84. U.S. Environmental Protection Agency. Lithium-Ion Battery Recycling. Available online: https://www.epa.gov/hw/lithium-ion-battery-recycling (accessed on 7 August 2024).
85. Miao, Y.; Hynan, P.; von Jouanne, A.; Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies* **2019**, *12*, 1074. [CrossRef]
86. Nickel—Element Information, Properties and Uses | Periodic Table. Available online: https://www.rsc.org/periodic-table/element/28/nickel (accessed on 7 August 2024).
87. Cobalt Statistics and Information | U.S. Geological Survey. Available online: https://www.usgs.gov/centers/national-minerals-information-center/cobalt-statistics-and-information (accessed on 7 August 2024).
88. Graphite—Definition, Structures, Applications, Properties, Use with Videos and FAQs of Graphite. Available online: https://byjus.com/chemistry/graphite/ (accessed on 7 August 2024).
89. Yang, J.-L.; Zhao, X.-X.; Li, W.-H.; Liang, H.-J.; Gu, Z.-Y.; Liu, Y.; Du, M.; Wu, X.-L. Advanced Cathode for Dual-Ion Batteries: Waste-to-Wealth Reuse of Spent Graphite from Lithium-Ion Batteries. *eScience* **2022**, *2*, 95–101. [CrossRef]
90. Rey, I.; Vallejo, C.; Santiago, G.; Iturrondobeitia, M.; Lizundia, E. Environmental Impacts of Graphite Recycling from Spent Lithium-Ion Batteries Based on Life Cycle Assessment. *ACS Sustain. Chem. Eng.* **2021**, *9*, 14488–14501. [CrossRef]
91. Mamidi, S.; Pandey, A.K.; Pathak, A.D.; Rao, T.N.; Sharma, C.S. Pencil Lead Powder as a Cost-Effective and High-Performance Graphite-Silica Composite Anode for High Performance Lithium-Ion Batteries. *J. Alloys Compd.* **2021**, *872*, 159719. [CrossRef]

92. Lithium Ion Battery Recycling. Available online: https://www.cas.org/resources/cas-insights/lithium-ion-battery-recycling (accessed on 7 August 2024).
93. Recycling Facts from around the World—Purpose Rising Blog. Available online: https://repurpose.global/blog/post/recycling-facts-from-around-the-world (accessed on 7 August 2024).
94. EU: Recycling Rate of Municipal Waste. Available online: https://www.statista.com/statistics/632839/municipal-waste-recycling-eu/ (accessed on 7 August 2024).
95. Kappalman, S. Updated Report: The West Coast Contamination Initiative: Results from California, Oregon, and Washington. Available online: https://recyclingpartnership.org/blog-the-west-coast-contamination-initiative-results-from-california-oregon-and-washington/ (accessed on 7 August 2024).
96. New Survey Discovers Why Most People Don't Recycle | WANE 15. Available online: https://www.wane.com/news/new-survey-discovers-why-most-people-dont-recycle/ (accessed on 7 August 2024).
97. 50 States of Recycling. Available online: https://www.ball.com/sustainability/real-circularity/50-states-of-recycling (accessed on 10 August 2024).
98. Lithium Mining Projects May Not Be Green Friendly—The New York Times. Available online: https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html (accessed on 7 August 2024).
99. Williams, B.D.; Lipman, T.E. Strategy for Overcoming Cost Hurdles of Plug-In–Hybrid Battery in California: Integrating Post-Vehicle Secondary Use Values. *Transp. Res. Rec.* **2010**, *2191*, 59–66. [CrossRef]
100. Ng, M.-F.; Zhao, J.; Yan, Q.; Conduit, G.J.; Seh, Z.W. Predicting the State of Charge and Health of Batteries Using Data-Driven Machine Learning. *Nat. Mach. Intell.* **2020**, *2*, 161–170. [CrossRef]
101. Sun, S.; Jin, C.; He, W.; Li, G.; Zhu, H.; Huang, J. Management Status of Waste Lithium-Ion Batteries in China and a Complete Closed-Circuit Recycling Process. *Sci. Total Environ.* **2021**, *776*, 145913. [CrossRef]
102. Ozymy, D.J.; Ozymy, D.M.J. Toxic Criminals: Prosecuting Individuals for Hazardous Waste Crimes Under the United States Resource Conservation and Recovery Act. *Sustain. Dev. Law Policy* **2023**, *23*, 5.
103. House, T.W. Fact Sheet: The Bipartisan Infrastructure Deal. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/ (accessed on 7 August 2024).
104. Here's What the Future of Battery Recycling Is Going to Look like for EV Owners | Electrek. Available online: https://electrek.co/2022/03/21/heres-what-the-future-of-battery-recycling-is-going-to-look-like-for-ev-owners/ (accessed on 7 August 2024).
105. Heath, G.A.; Ravikumar, D.; Hansen, B.; Kupets, E. A Critical Review of the Circular Economy for Lithium-Ion Batteries and Photovoltaic Modules—Status, Challenges, and Opportunities. *J. Air Waste Manag. Assoc.* **2022**, *72*, 478–539. [CrossRef]
106. Slattery, M.; Dunn, J.; Kendall, A. Charting the Electric Vehicle Battery Reuse and Recycling Network in North America. *Waste Manag.* **2024**, *174*, 76–87. [CrossRef]
107. Meng, K.; Xu, G.; Peng, X.; Youcef-Toumi, K.; Li, J. Intelligent Disassembly of Electric-Vehicle Batteries: A Forward-Looking Overview. *Resour. Conserv. Recycl.* **2022**, *182*, 106207. [CrossRef]
108. All Our Patent Are Belong to You. Available online: https://www.tesla.com/blog/all-our-patent-are-belong-you (accessed on 7 August 2024).
109. Chirumalla, K.; Kulkov, I.; Parida, V.; Dahlquist, E.; Johansson, G.; Stefan, I. Enabling Battery Circularity: Unlocking Circular Business Model Archetypes and Collaboration Forms in the Electric Vehicle Battery Ecosystem. *Technol. Forecast. Soc. Chang.* **2024**, *199*, 123044. [CrossRef]
110. Kia Establishes Multi-Stakeholder Partnership to Drive Circular Economy in EV Battery Industry. Available online: https://www.kianewscenter.com/images-and-videos/image/kia-establishes-multi-stakeholder-partnership-to-drive-circular-economy-in-ev-battery-industry/a/5013cf97-2b59-43bd-a4a1-bd803cb3ced3 (accessed on 7 August 2024).
111. Zhang, Q.; Tang, Y.; Bunn, D.; Li, H.; Li, Y. Comparative Evaluation and Policy Analysis for Recycling Retired EV Batteries with Different Collection Modes. *Appl. Energy* **2021**, *303*, 117614. [CrossRef]
112. Balachandran, S.; Forsberg, K.; Lemaître, T.; Vieceli, N.; Lombardo, G.; Petranikova, M. Comparative Study for Selective Lithium Recovery via Chemical Transformations during Incineration and Dynamic Pyrolysis of EV Li-Ion Batteries. *Metals* **2021**, *11*, 1240. [CrossRef]
113. Boyo, S. Here's How EV Batteries Can Be Given a Second Life. Available online: https://www.cnbc.com/2023/03/29/heres-how-ev-batteries-can-be-given-a-second-life.html (accessed on 7 August 2024).
114. Bajolle, H.; Lagadic, M.; Louvet, N. The Future of Lithium-Ion Batteries: Exploring Expert Conceptions, Market Trends, and Price Scenarios. *Energy Res. Soc. Sci.* **2022**, *93*, 102850. [CrossRef]
115. Identifying Government Grants and Funding Opportunities. Available online: https://fastercapital.com/keyword/identifying-government-grants-and-funding-opportunities.html (accessed on 10 August 2024).
116. Meticulous Market Research Pvt. Ltd. EV Battery Recycling Market to Be Worth $15.8 Billion by 2030—Exclusive Report by Meticulous Research®. Available online: https://www.globenewswire.com/en/news-release/2023/03/23/2633129/0/en/EV-Battery-Recycling-Market-to-be-Worth-15-8-Billion-by-2030-Exclusive-Report-by-Meticulous-Research.html (accessed on 7 August 2024).
117. Luo, D. Research on the Influence of Consumers' Environmental Preference and Government Policy on EV Battery Recycling. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *651*, 042057. [CrossRef]

118. Cox Automotive Mobility Takes Charge of EV Battery Lifecycle Services with Global Acquisition—Cox Automotive Inc. Available online: https://www.coxautoinc.com/news/cox-automotive-mobility-takes-charge-of-ev-battery-lifecycle-services-with-global-acquisition/ (accessed on 7 August 2024).
119. The US Lags on Battery Sustainability and Supply Chain Transparency—Can a Digital 'Passport' Be the Answer? Available online: https://www.utilitydive.com/news/battery-sustainability-supply-chain-passport-tesla/642541/ (accessed on 7 August 2024).
120. Policies to Promote Electric Vehicle Deployment—Global EV Outlook 2021—Analysis. Available online: https://www.iea.org/reports/global-ev-outlook-2021/policies-to-promote-electric-vehicle-deployment (accessed on 7 August 2024).
121. Michigan Workforce Hub Will Focus on EVs, Training. Available online: https://www.govtech.com/transportation/michigan-workforce-hub-will-focus-on-evs-training (accessed on 10 August 2024).
122. House, T.W. FACT SHEET: The Biden-Harris Electric Vehicle Charging Action Plan. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/13/fact-sheet-the-biden-harris-electric-vehicle-charging-action-plan/ (accessed on 7 August 2024).

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