clean technologies

MDPI

Review

End-of-Life Management of Electric Vehicle Lithium-Ion Batteries in the United States

Jay N. Meegoda *, Sarvagna Malladi and Isabel C. Zayas

Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA
* Correspondence: jay.meegoda@njit.edu or meegoda@njit.edu

Abstract: Electric vehicles, which are primarily powered by lithium-ion batteries, have gained much attention as the future of transportation for their environmental and economic benefits. However, the current economy of lithium-ion battery management is quite linear. A circular economy with reusing and end-of-life recycling of lithium-ion batteries, would reduce the social and environmental costs associated with the mining of metals, decelerate the depletion of natural resources, and prevent the improper management that often accompanies disposal. This research suggests improvements to the end-of-life management of lithium-ion batteries in the US, considering current and emerging recycling technologies, current collection and transportation infrastructure, current reuse applications, and an analysis of the current regulatory policies in place. Along with providing a comprehensive overview of these topics, this research compiles and provides a set of actionable End-of-Life (EOL) management recommendations for the US on policy, infrastructure, and technology.

Keywords: electric vehicles; lithium-ion batteries; circular economy; recycling; reuse; collection and transportation infrastructure; policy and regulations

check for updates

Citation: Meegoda, J.N.; Malladi, S.; Zayas, I.C. End-of-Life Management of Electric Vehicle Lithium-Ion Batteries in the United States. *Clean Technol.* **2022**, *4*, 1162–1174. https://doi.org/10.3390/cleantechnol4040071

Academic Editor: Patricia Luis

Received: 8 August 2022
Accepted: 7 November 2022
Published: 14 November 2022

1. Introduction

The use of electric vehicles (EVs) has been recognized as a key method for reducing air pollution and greenhouse gas emissions. Electric vehicles have zero tailpipe emissions as well as a smaller carbon footprint, if renewable power is used to recharge, over the course of their lifetime when compared to vehicles using traditional internal combustion engines [1]. Lithium-ion batteries (LIBs) are the primary type of battery used in EVs and will thus be the focus of this research [2–4]. In August 2021, US President Biden set a target for half of all new vehicle sales by 2030 to be zero-emission vehicles, primarily electric cars and trucks [2]. This projected increased adoption of EVs raises important questions about the availability and sustainability of the raw materials used for LIBs that will be powering them.

Without a standardized system, the materials used in these batteries will quickly end up in landfills. Irregular disposal of spent batteries can lead to fire hazards and the leaching of toxic substances into the environment. In the case of lithium-ion batteries, lithium cobalt oxide and lithium manganese oxide are used as cathodes, as well as lithium hexafluoride phosphate, lithium tetrafluoride borate, and other lithium salts as electrolytes. These materials are not only hazardous, but they are also valuable. If they are lost due to improper disposal, manufacturers will be forced to keep extracting new materials from the ground. Such action not only depletes nonrenewable resources, but it harms those living in the countries where mining takes place, as the labor often is performed by children and is done under dangerous conditions. Additionally, the dust from explosives used in mining, as well as the sulfuric acid used for mining and processing operations, are linked to health problems including respiratory diseases and birth defects.

2. Why Improving EOL Management and Developing a Circular Economy Is Important

The current LIB economy is quite linear, with batteries being disposed of at their end of life. This not only results in environmental pollution but also causes rapid resource depletion. Figure 1 shows the current linear economy for lithium-ion electric vehicle batteries.

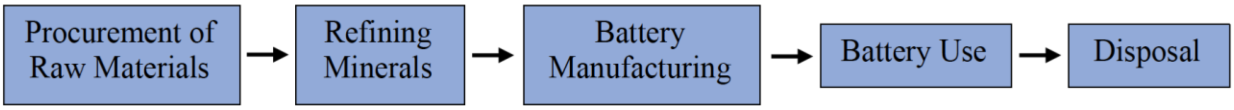

Figure 1. Current linear economy for lithium-ion electric vehicle batteries.

Making the LIB economy more sustainable will require converting it to a circular economy. Through a circular economy, the EOL LIB is reused and/or recycled in order to harness the maximum potential from the LIB before it is ultimately disposed of. Figure 2 shows the potential circular economy for lithium-ion electric vehicle batteries.

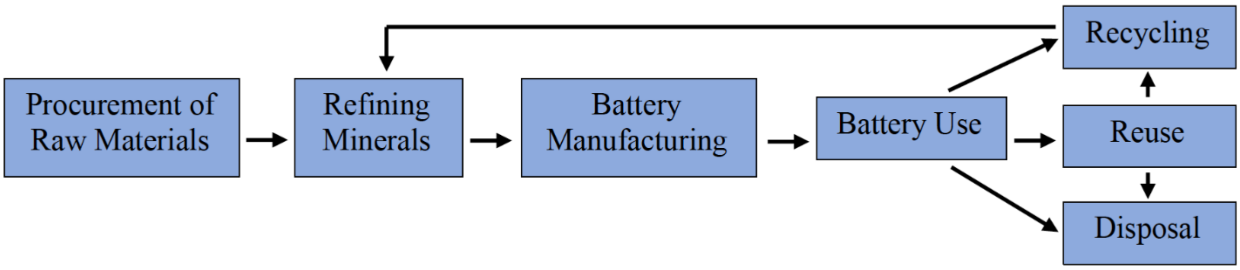

Figure 2. Potential circular economy for lithium-ion electric vehicle batteries.

An important step in establishing a circular LIB economy will be refining the processes associated with reuse and recycling, and ensuring these processes smoothly feed back into the economy. This will require technological innovation especially green technology, along with policy and regulatory steps, which is the focus of this manuscript.

2.1. Raw Material Demand Caused by Mining

Figure 3 shows the outlook for global passenger car production with three potential future projections. The initial red curve of Figure 3 has been produced using a dataset for world passenger car production from 1994 to 2020 compiled by the Bureau of Transportation Statistics (BTS) [3]. It is important to note that the BTS does not include “minivans, pickups, and sport utility vehicles” in the passenger car category and excludes commercial vehicles from the data. In addition, some smaller countries have not been listed in the table for world totals. The later blue curve of the graph is a projection of global passenger car production until 2030, created using a line of best fit. The lower blue curve would be assuming the current global semiconductor shortage coupled with the impact of the pandemic. The middle curve was proposed by BTS and the upper blue curve are the best possible outcome with federal incentives. Using the outlook from Figure 3, approximately 450 million new passenger cars will be produced between 2022 and 2030.

The World Resources Institute (WRI) proposes that “growth in sales of electric vehicles is likely to follow an S-Curve or market diffusion curve.” Figure 4 shows a S-curve, developed from historic, projected, and benchmark data provided by Climate Action Tracker [5] and based on the graph created by the WRI [6] that demonstrates the growth trend of passenger EVs that is necessary to meet the 2035 benchmark in the United States. Using this projection, about 225 million passenger vehicles—an average of 50% of the 450 million new passenger vehicles—will be electric vehicles. Though the quantity of metals that need to be mined for electric vehicles vary depending on the battery type and model of the vehicle, based on Castelvecchi [7] and data from Argonne National Laboratory, “a single car lithium-ion battery pack, of a type known as NMC532, could contain around 8 kg of lithium, 35 kg of nickel, 20 kg of manganese and 14 kg of cobalt." The NMC batteries are the most common type of battery for electric vehicles.

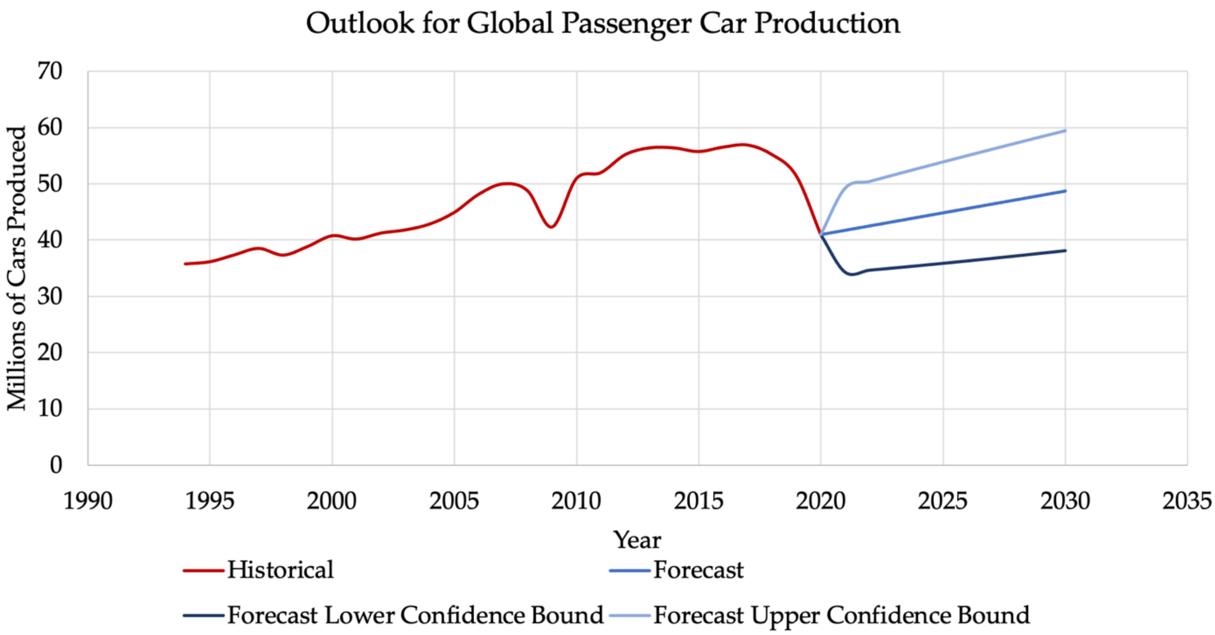

Figure 3. Outlook for global passenger car production with three potential projections.

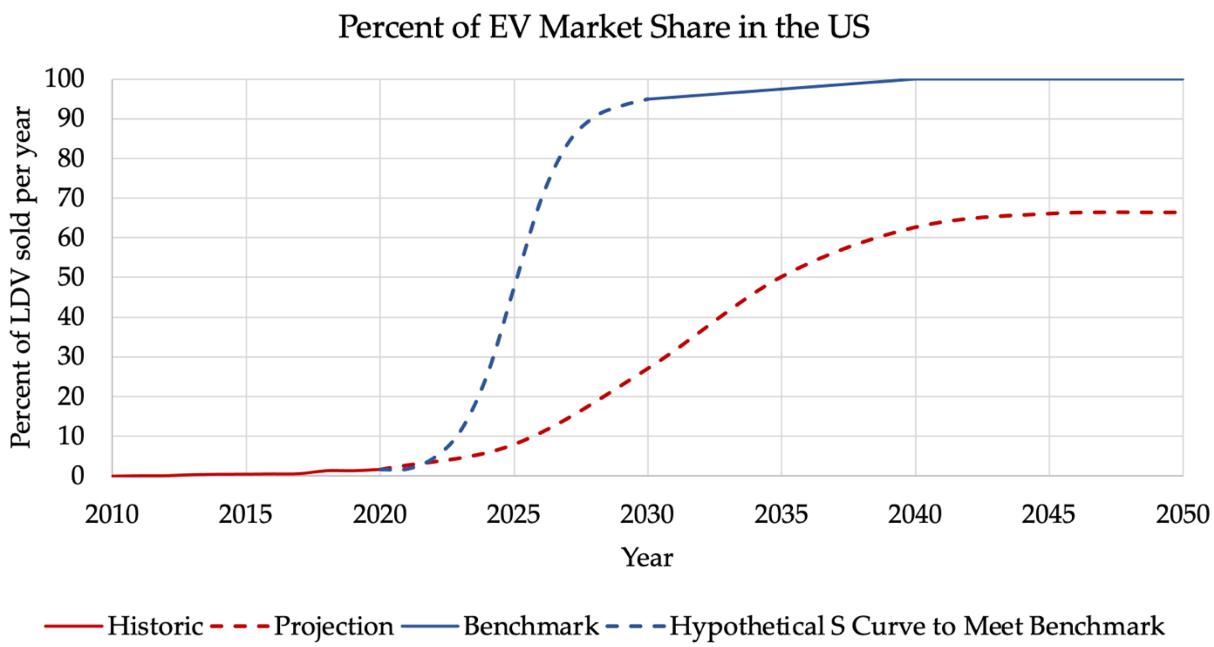

Figure 4. A S-curve created with data from Climate Action Tracker [5] and based on that made by the WRI [6] to demonstrates the growth of passenger EVs.

Thus, the required projection of 225 million new battery packs would demand 1.8 million metric tons of lithium, 7.9 million metric tons of nickel, 4.5 million metric tons of manganese, and 3.2 million metric tons of cobalt. According to the USGS, identified worldwide cobalt resources, including mine production and reserves, only total around 8 million metric tons [8]. Thus, it is clear that the production of LIBs alone would use up 40% of the identified cobalt resources, assuming that the chemistry of these batteries does not change, and the EV share of global new passenger vehicle sales follows the projected path. It should be noted that this estimated resource demand does not include lithium-ion battery demand from commercial cars or other vehicles. It also does not consider the other major cobalt-reliant sectors, such as superalloy, hard materials, and ceramics and pigment. Ensuring the reuse and recycling of EOL LIBs will keep high-demand metals like cobalt in circulation and prevent rapid resource depletion.

2.2. Environmental Impacts of Mining

Lithium extraction is another concern as it often results in environmental degradation. Two of the top lithium sources are in Australia and Chile [9]. Butt et. al., 2022 performed an in-depth study and showed the detrimental environmental impacts of the current lithium harvesting technologies [10]. According to Butt et. al., 2022, 59% of lithium is extracted from naturally occurring salt deposits [10]. First, a naturally occurring salt is converted to a concentrated brine solution and pumped out of the ground [11]. The solution is then poured into large, shallow ponds to evaporate the excess water, after which the remaining lithium compound is purified and processed. This method is quite energy-intensive due to the machinery required to pump the brine solution out of the ground. Additionally, because this method relies on rapidly evaporating large pools of brine, it quickly depletes the surrounding water supply.

Furthermore, Butt et. al., 2022, states that 25% of lithium is extracted from lithium-bearing mineral clays such as lepidolite and zinnwalidite [10]. Some of the commonly used methods to harvest lithium from these clays are chemical leaching, bioleaching, and pressure leaching. Though all of these processes have a nearly perfect purity rate of 99%, they are also relatively energy intensive as well. Furthermore, they require the heavy usage of chemicals, which if not properly disposed of, can seep into surrounding waterways and natural habitats [11].

Though cleaner harvesting techniques, such as ion-selective nanostructured membranes are emerging [10], it is likely that it will take time for extraction companies to switch to these less conventional methods. Thus, recovering and using the recycled material from LIBs will place less demand on extracting raw lithium, thereby mitigating the harmful environmental effects that often accompany extracting lithium from the environment.

2.3. Social Impacts of Mining

The social toll of extracting LIB metals is also concerning. About 20–30% of the cobalt that the Democratic Republic of Congo produces comes from small-scale, artisanal mining, where there are minimal labor laws and safety protocols. There are over 200,000 artisanal miners, including at least 40,000 children. Child laborers dig for crustal rock, which contains cobalt, under inhumane conditions. They receive little to no protective equipment and work in low oxygen levels, although they make as little as one dollar a day [12]. It is estimated that around 2000 miners die each year in the Congo, while other workers suffer permanent lung damage, skin conditions, and permanent injuries [12]. Banza Lubaba Nkulu et al., 2018, showed that in the town of Kolwezi, "people living in a neighborhood that had been transformed into an artisanal cobalt mine had much higher levels of cobalt in their urine and blood than people living in a nearby control area" [13]. Several US EV manufacturers, including Tesla and Volkswagen, often source their cobalt from Chinese-owned mines in the Congo [12]. This is due to the lower cost of buying cobalt from an unregulated mine than from a regulated mine, as labor costs are less at the former. As the demand for new LIBs increases, so will the likelihood that a larger percentage of cobalt will come from unethically sourced labor. Transitioning away from a linear LIB economy will keep metals like cobalt in circulation, thus reducing the amount of new cobalt bought from unregulated mines and limiting the human costs of mining.

2.4. Landfill Concerns

LIBs that are not recycled or reused may be improperly landfilled rather than being disposed of at hazardous waste collection facilities. This can lead to destructive fires.

According to the USEPA, there were more than 240 fires caused by LIBs at 64 facilities between 2013 and 2020 [14]. Though many of these fires were caused by LIBs from small consumer devices, such as cellphones and laptops, LIBs from EVs could make up a larger percentage of fires in the future if they continue to be landfilled. Increasing recycling and reuse will prevent many LIBs from being incorrectly disposed of at their EOL.

3. Recycling

Most EOL LIBs are ultimately sent to be recycled, whether or not the battery has already been reused or refurbished. The conventional recycling processes used on an industrial scale include pyrometallurgical (pyro) and hydrometallurgical (hydro) processes. These depend largely on the recovery of cobalt, the main cost driver, as the key contributor to revenue. The aforementioned common industry scale recycling process, primarily hydrometallurgy or a combination of hydro and pyro methods [15], also can recover lithium and nickel [16]—materials that, though not as costly as cobalt, are not of negligible cost. These recovered metals can similarly be used in production of cathodes as well. The use of cobalt in cathode formulations is decreasing rapidly, however, which means that these methods may soon lose some of their competitive edge. Additionally, the metals recovered from pyro and hydro processes require further refining before they can be used to manufacture new batteries [17]. Please note that the process parameters and the properties of directly recycled materials reported in the literature differ greatly [18–20]. Hence, pyrometallurgy and hydrometallurgy are being usually operated at the industrial level, and direct recycling described below is only at the lab and pilot scale.

Direct cathode recycling, another method of recycling, depends on the recovery of the cathode of a battery, whether it contains cobalt or not. This method retains the structure of the cathode, rather than breaking it down into constituent elements, which means it can be used for any cathode chemistry. However, it does require disassembly and faces barriers including sorting and labor costs, making it more difficult to achieve on the larger scales of hydro and pyro recycling unless fully automated, despite growing interest in this process [15]. Lithium iron phosphate (LFP) batteries are better suited to the direct recycling process as well, as the valuable cathode materials here are best recovered using this process [21], therefore, the barriers mentioned in direct recycling of LIBs also effect the recycling of LFPs. In a paper published in the scientific journal Energy Technology, a direct cathode recycling process called froth flotation was detailed [22]. This process separates individual cathode materials in a flotation tank which has negligible impact on the performance of the cathode materials and has high purity levels. It is also far less energy-intensive and does not require expensive equipment required for pyro and hydro processes. Harper et al., 2019 [23], Kallitsis et al., 2022 [24], and Chen et al., 2019 [25] provide comprehensive analysis on recycling lithium-ion batteries from electric vehicles.

4. Transportation Infrastructure

LIBs are treated as hazardous waste due, largely, to their potential to cause fire, though they do not contain the hazardous substances that can be found in other types of batteries, such as sulfuric acid, cadmium, and lead. LIB disposal confronts expensive restrictions, for example, hazardous waste can only be transported at designated times, picked up at certain locations, and transported via select routes in selected containers.

The fact that LIBs can only be shipped in specially designed cases results in transportation costs making up about 40 percent of the overall cost of recycling [26]. Due to this, sometimes transportation costs can exceed those of extracting new materials from the ground. One option to bring down these transportation costs is to increase the number of LIB recycling centers so that there is less distance to cover when transporting them. This is further discussed under the section of policy and regulations.

5. Collection Infrastructure

The USEPA recommends that consumers wishing to recycle their electric vehicle batteries should first contact the automobile dealer or shop where the battery was purchased [14]. However, there is not yet a standardized process to recycle these batteries. Instead, the drop-off process and costs differ from facility to facility. For LIB reuse and recycling to be efficient and standardized, an established collection infrastructure to bring EOL LIBs to a few central locations from which they can be transported to reuse companies or recyclers is needed. This collection infrastructure does not currently exist in the US—instead, LIBs are scattered in small numbers in many locations throughout the country [27].

6. Reuse

The EOL LIBs still have significant remaining capacity, around 70% to 80% once they are removed from an EV [27]. Reusing EOL LIBs in "second life" applications can help to extend the usable life of a battery before it is ultimately recycled. The Lithium iron phosphate batteries also have similar second life in energy storage systems issues as in LIBs [28].

6.1. Reuse in Electric Vehicles

Many auto-repair shops and auto mechanics sell EOL LIBs to operators who create a new battery from the packs and cells that have sufficient remaining capacity through a process known as refurbishment [27]. During the refurbishment, the functional cells in LIBs are recovered and used. The operators then resell this refurbished battery to consumers.

6.2. Reuse in Energy Storage Systems (ESSs)

EOL LIBs could also be used in home energy storage systems, including solar PV systems [29]. However, according to Tesla's former Chief Technology Officer and founder of Redwood Materials, Mr. Straubel, one of the largest barriers to reusing batteries in ESSs is the rapidly changing battery storage technologies. Some technologies currently in use are outlined in Table 1 below. The technology found in LIBs will be almost a decade old by the time they would make it to the second-use market. Thus, many reused batteries are not expected to be compatible with future storage systems. This problem will likely iron itself out over the next few decades as the technology used in LIBs is standardized.

Table 1. Outline of Some Current ESS Battery Technologies.

ESS Battery Type	Advantages	Disadvantages
Redox Flow Batteries Iron Flow Batteries Vanadium Redox Batteries	• Long service life [30] • Safety—not flammable or explosive [30] • Power generation is cost effective [30] • Battery chemistry made with simple, non-toxic, materials (iron, water, electrolyte) [31] • Long Duration (6–12 h) [31] • Easy electrolyte recycling after 25-year design lifespan [31] • Stable ions allow for many cycles with little unfavorable side effects [32] • Currently less expensive than new LIBs [33]	• Complex system [30] • Lower energy density than LIBs [32] • Large external tanks required [32] • Lower rates of charge and discharge [34] • High cost of Vanadium [32]
Lead-Acid Batteries	• Low manufacturing costs [30] • High discharge current capacity [30] • Little impacts from ambient temperature [30]	• Slow charging [30] • Contains toxic materials [30] • Limited life cycle [30]

Table 1. *Cont.*

ESS Battery Type	Advantages	Disadvantages
Lithium-Ion Batteries	• Refurbished LIB batteries are cost effective compared to new LIB batteries [35] • Creates second life option for battery rather than using newly manufactured battery [33] • Relatively short charging times [30]	• Possible increased maintenance costs over course of second life [33] • Possibly better suited for smaller scale ES systems [33] • Rapid charging effected by ambient temperature [30] • Transportation regulations [30] • Safety—short circuit or fire potential

6.3. Potential Risks

Refurbished batteries are a promising solution to extend the lifetime of a LIB but combining cells of different ages and capacities without a proper battery management system or proper ventilation can lead to overheating and could even cause fires [36]. Thus, a system must be developed to ensure that batteries that are placed in the same module are compatible with one another. Additionally, the issue of liability is a large barrier facing reuse, as repurposed batteries have a greater risk of failure. If the batteries fail in a way that causes harm to human health or the surrounding environment, it is difficult to trace back the battery to the original manufacturer with the current tracking system [27]. Possible ways to prevent these risks are proposed in the following section on policy and regulations.

7. Policy and Regulations

7.1. Comparison of the Regulatory Landscape in the US and in Other Regions of the World

7.1.1. European Union

In 2020, it was proposed that the EU's 2006 Battery Directive, which, due to its vague nature, has been interpreted and implemented in various ways by member states, be replaced with a new Battery Regulation that would be more specific to LIBs. According to Stena Recycling, the Battery Regulation proposes "79 binding articles will prevent EU countries from implementing the legislation in different ways" [37]. The regulation covers all types of portable, starter, vehicle, and industrial batteries, which includes the LIBs used in EVs. "These new requirements will affect the manufacture, design, labeling, traceability, collection, re-use, and recycling of batteries throughout their lifecycle." This regulation is expected to come into effect between 2022 and 2023.

There are several key features of the EU Battery Regulation. It mandates extended producer responsibility (EPR) for proper EOL management and transfer of EPR [26] and the following are some of the specifics:

- Producers must organize and finance the collection, treatment, and recycling of waste batteries.
- They must also take back any waste batteries free of charge, without requiring end-users to buy a new battery or to have bought the battery from them.
- It places responsibility on LIB battery manufacturers to label batteries and provide instructions on how to handle the batteries including EOL management. It also plans to implement an electronic battery passport.
- Labeling Conventions:
  - The material content, the quantity of each material, and its origin should be indicated on automotive and industrial batteries [37].
  - From 2027, the EU will require batteries to be labelled with the name of the manufacturer, type of battery, date of manufacture, presence of hazardous substances, and other information that facilitates recycling or reuse [37].
- Documentation:

    - It requires reconditioned or reused batteries to be accompanied by documentation regarding their status, a change of ownership certificate, and technical documentation [37].
    - The regulation places responsibility on manufacturers to provide proper instructions. Manufacturers will be required to provide information on how automotive batteries should be safely dismantled, transported, and recycled and must disclose the environmental and health impact of battery contents [37].
- The regulation also proposes the adoption of an electronic battery passport. The EU will introduce an electronic battery passport for industrial and automotive batteries with a capacity of 2 kWh or more, which will contain all available information on each battery. When the status of the battery changes (e.g., due to repair or reuse), this information will need to be updated [37].

The EU regulation aims to increase recycling and reuse and places more responsibility on recycling facilities. Recyclers will have to report annually on the number of batteries they handle and recycle, as well as the recycling rates of the various materials extracted [37]. They will also need to measure and report the efficiency of their recycling processes. The regulation also sets clear recycling goals. From 2025, 65% of LIB weight must be recycled, which will increase to 70% in 2030 [37]. Specific recycling requirements will be introduced for the lithium, cobalt, copper, nickel, and lead components of batteries. For example, the required recycling rate for lithium will increase from 35 to 70% between 2026 and 2030. The EU is seeking to set a 90% recycling rate for cobalt, copper, nickel, and lead from 2026 [37]. Finally, the regulation ensures that all batteries are accounted and the export of used batteries outside the EU will only be permitted if the recipient's battery management procedure meets EU's requirements [37].

The EU's Battery Regulation will prioritize an increased use of recycled raw materials in manufactured batteries. As early as 2027, the proposed EU legislation will require manufacturers to provide transparent information on the quantity of recycled cobalt, lithium, nickel, and lead in new car batteries. The required amount of recycled cobalt and lithium will more than double from 2030 to 2035." [37]

Finally, steps will be taken to re-locate more of the battery value chain—the European Commission identified the importance of locating more of the battery value chain within the region, including raw material extraction and battery production [26].

7.1.2. China

China is another leading country that is promoting sustainable EOL use for LIBs. Like the EU, it acknowledges the concept of EPR. In 2017, China enacted the Promotion Plan for Extended Producer Responsibility System, which proposed the creation of a LIB recycling system based on the EPR principles [26]. It has also implemented a pilot EV Recycling Initiative in 17 cities/regions, controlling the number of new enterprises involved in recycling to make full use of existing infrastructure [26]. China also aims to improve traceability through its Battery Traceability Management Platform, the purpose of which is to better track LIBs throughout their life cycle [26]. China has placed more responsibility on manufacturers to label/design their batteries in a recyclable-friendly way. In 2018, it enacted the Interim Measures for the Management of Recycling and Utilization of Power Batteries of New Energy Vehicles, which requires manufacturers to help recycling companies by labeling batteries and using designs that are easier to recycle [26]. Finally, China has also restricted reuse in certain applications, putting forth a policy proposing to temporarily ban the use of repurposed batteries in large-scale energy storage applications for two main reasons:

- Using old batteries may lead to higher operational costs than using new batteries.
- Used batteries arrive at storage facilities at different stages of use, meaning these facilities need to spend more time/money to standardize these batteries.

7.1.3. Other International Efforts

There have been many international efforts to promote a circular economy for EOL of LIBs that come from EVs. One such effort is the Global Battery Alliance (GBA), which has supported the development of the recently commercialized Battery Passport. The Battery Passport is a solution to improve the traceability of batteries. It will be used by the EU and is supported by the current Canadian and US administrations.

The Battery Passport is a digital representation of each battery and provides a digital ID. It contains information about battery health and manufacturing for the purpose of deciding whether the battery is suitable for reuse. The data provided by the Battery Passport is valuable for determining whether a battery should be repurposed or recycled after its first use and provides with reliable and detailed information about battery health before purchasing and testing [38].

7.1.4. US

Currently, US federal law is relatively weak with respect to the reuse and recycling of EOL management of LIBs. However, some already passed laws can be applied to LIBs. There are pre-existing regulations under which EV car batteries fall, especially in their recycling, as mandated by 40 CFR §§ 264, 265, 266, 268, 270, and 124 [26]. Likewise, there exist provisions under RCRA which target the handling and export of regulated wastes [26]. Though the US is lacking in explicit policies, there is some attention towards R&D and the creation of task forces. For example, the US Department of Energy has a Battery Recycling Prize competition to fund entrepreneurs developing lithium-ion battery recycling technologies. Additionally, the H.R.1512 CLEAN Future Act proposes the creation of a task force to make recommendations for how to design systems to improve battery lifecycle management [39].

Policies in Different States of US

Varying levels of LIB management policies exist across US states, but federal regulations require state standards to be either identical or more stringent. Thus, certain states, such as California, have taken the initiative to implement more strict regulations regarding LIB EOL management. California has passed regulations relevant to the proper disposal of LIBs, regulating activities such as dismantling, transportation, storage, disassembly, installation into Energy Storage Systems, hazardous waste treatment, and export. Below are two excerpts that pertain to recycling and reuse:

- Recycling: The Standards for Universal Waste Management in 40 CFR § 273, Subpart E states the destination facilities are required to follow the hazardous waste treatment regulations and destination facilities are defined as a facility that treats, disposes of, or recycles universal waste, therefore it covers the recycling of the batteries [26].
- Reuse: There are respective tariffs that batteries connected to the electricity grid within California must comply with. The three categories of ESS applications are (1) Net-energy metering/non-export facility, (2) Wholesale market, connected to distribution system, and (3) Wholesale market, connected to transmission system [26].

Though these regulations do ensure proper and safe handling of the EOL LIB management chain, they do not set any quantitative goals for recycling nor encourage circular partnerships between manufacturers and recycling facilities to reach these goals.

In 2018, California created a Lithium-Ion Car Battery Recycling Advisory Group to provide policy recommendations to the legislature, which are expected in 2022. Additionally, in 2022 the state of CA enacted the end date for sale of vehicles with internal combustion engines, but still lacks policies or regulations for EOL management of LIBs used in EVs.

7.2. Improvements to US Policy

The distinction between policies in the United States and the EU as well as China is that, in the US, while regulations exist concerning activities related to the handling of EV car batteries at their end of life, there is a need for recycling and reuse targets, as well as steps for achieving the following targets:

- Ensuring Extended Producer Responsibility (EPR) to finance recycling and collect batteries from consumers free of charge.
- Increasing battery traceability through a battery passport infrastructure.
- Increasing recycling and reuse by setting requirements for recycling facilities and setting clear goals.
- Increasing the use of recycled raw materials by setting requirements for battery manufacturers to use a specified percentage of recycled material in batteries.
- Ensuring that manufacturers design and label batteries to ease the recycling and reuse processes, either through financial incentives or enforced policies.

These steps must be implemented in a specific LIB battery manufacturer's design as proof of concept to avoid confusion between the various battery technologies and chemistries. There are also several infrastructure changes that must be implemented to support the development of a circular economy for LIBs.

Specifically in the US, recycling facilities are limited in both number and processing capacity. Encouraging the building of additional recycling facilities with larger capacity in the US or utilizing battery recycling centers overseas that have enough capacity to reach recycling targets, will be critical. According to UCSUSA, globally, fewer than a dozen facilities recycle LIBs today, with a combined material processing capacity of less than 100,000 metric tons annually [40]. For 50 kWh batteries with a gravimetric energy density of 150 watt-hours per kilogram, this recycling capacity corresponds to 300,000 LIBs per year, or roughly 10 percent of global annual EV sales today, but 1 percent of expected annual sales in the early 2030s [40]. Additionally, it must be ensured that LIB manufacturers comply with battery passports, allow batteries to be tracked with said passports, collect batteries, use recycled materials in new batteries, and finance/encourage recycling.

8. Discussion

Recycling of EOL batteries is an essential strategy to recover the metals used during manufacturing, as studies have shown that recycled batteries can perform as well. One emerging recycling technology is direct cathode recycling, which includes methods such as froth flotation. Compared to recycling processes such as hydrometallurgy, developing direct cathode recycling may be a more realistic option long-term, considering that LIB technology is evolving to minimize the amount of cobalt used during manufacturing.

Reuse of LIBs, especially in energy storage systems and electric vehicles, is another sustainable EOL path that can extend the usable life of a battery. However, the lack of proper labeling and management, knowledge regarding which batteries are safe to keep with each other, and tracking systems, are all serious current liability concerns.

Making transportation and collection more accessible, while still ensuring safety and efficiency, will incentivize sustainable EOL paths such as reuse and recycling. Potential changes include increasing the number of recycling centers in each state or create regional facilities and establishing several central collection locations for battery drop-off. Additionally, modifying recycling policies for LIBs specifically, to make transportation requirements less stringent, would ease the financial and time burden that often accompanies the transport of LIBs. This will provide an incentive for consumers, manufacturers, and other EOL handlers to reuse and recycle batteries. Based on the current composition of most LIBs, it is possible to recycle up to 70% of material used in LIB causing only 30% waste. New LIB manifesting technology should consider green technology to increase the above to 95% or higher.

Regions such as the European Union and China have been quite progressive in their LIB regulation. After an extensive review and summary of these policies, it is clear that some key policy goals of the United States with respect to LIBs should be:

- Ensuring extended producer responsibility to finance recycling and collect batteries from consumers free of charge.

- Increasing battery traceability through battery passport infrastructure.
- Increasing recycling and reuse by setting clear goals and requirements for recycling facilities.
- Increasing the use of recycled raw materials by requiring battery manufacturers to use a specified percentage of recycled material in new batteries.
- Ensuring that manufacturers design and label batteries to ease the recycling and reuse processes, either through financial incentives or enforced policies.

9. Summary and Conclusions

Electric vehicles are projected to make up a large percentage of the future vehicle fleet, a fact that is reflected in the policies of many countries. These vehicles certainly have the potential to reduce emissions and become the future of transportation, but in order to make this potential a reality, the production and supply of EV batteries must also be scaled up. Considering the rapid resource depletion, unethical labor, and environmental degradation that often accompanies the production of new batteries, recycling and reuse are two viable options to mitigate the adverse impacts of battery production while meeting the demand for EV batteries in a sustainable manner.

Promoting recycling and reuse would require shifting LIBs from a linear economy to a circular economy, highlighting the need for simultaneous improvements to current recycling and reuse technologies, transportation and collection infrastructure, and regulatory landscape. Doing so would allow the US to better meet projected demand for electric vehicle batteries, as well as reducing the environmental and social destruction that often accompanies mining processes. Especially in policy and regulation, the US can look to examples set by the European Union and China, among others, to determine the most urgent aspects to address first. It is essential to take these technological, infrastructure, and regulatory steps before enacting an end date for vehicles with internal combustion engines, in order to avoid future issues with meeting the increasing demand for electric vehicles.

Author Contributions: Conceptualization, J.N.M.; Investigation, S.M. and J.N.M.; Writing—original draft preparation, S.M. and J.N.M.; Writing—review and editing, I.C.Z., S.M. and J.N.M.; Supervision, J.N.M.; Project administration, J.N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: This study did not involve humans.

Data Availability Statement: Not applicable.

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

References

1. UCSUSA. Now Is the Time for Heavy-Duty Electric Vehicles. Union of Concerned Scientist of USA. Available online: https://www.ucsusa.org/resources/ready-work (accessed on 8 July 2022).
2. Whitehouse. President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/ (accessed on 8 July 2022).
3. USDOT. World Motor Vehicle Production, Selected Countries. Bureau of Transportation Statistics. Available online: https://www.bts.gov/content/world-motor-vehicle-production-selected-countries (accessed on 8 July 2022).
4. USDOE. Batteries for Hybrid and Plug-In Electric Vehicles. Energy Efficiency and Renewable Energy. Available online: https://afdc.energy.gov/vehicles/electric_batteries.html (accessed on 8 July 2022).
5. Climate Action Tracker Data Portal. EV Market Share. Available online: https://climateactiontracker.org/data-portal/?sector=Transport%20Road&indicator=EV%20market%20share&country=US&scenario=historic&scenario=benchmark&scenario=projected_current_policy&mode=countries (accessed on 8 July 2022).
6. Kothari, V.; Sclar, R. Are We on the Brink of an Electric Vehicle Boom? Only with More Action. World Resources Institute. 2020. Available online: https://www.wri.org/insights/what-projected-growth-electric-vehicles-adoption (accessed on 8 July 2022).
7. Castelvecchi, D. Electric cars and batteries: How will the world produce enough? *Nature* **2021**, *596*, 336–339. Available online: https://www.nature.com/articles/d41586-021-02222-1 (accessed on 8 July 2022). [CrossRef] [PubMed]

8. USGS. *Mineral Commodity Summaries 2022*; U.S. Geological Survey: Reston, VA, USA, 2022.
9. Igogo, T.A.; Sandor, D.L.; Mayyas, A.T.; Engel-Cox, J. *Supply Chain of Raw Materials Used in the Manufacturing of Light-Duty Vehicle Lithium-Ion Batteries*; Clean Energy Manufacturing Analysis Center: Golden, CO, USA, 2019.
10. Butt, F.S.; Lewis, A.; Chen, T.; Mazlan, N.A.; Wei, X.; Hayer, J.; Chen, S.; Han, J.; Yang, Y.; Yang, S.; et al. Lithium Harvesting from the Most Abundant Primary and Secondary Sources: A Comparative Study on Conventional and Membrane Technologies. *Membranes* **2022**, *12*, 373. [CrossRef] [PubMed]
11. Coltura. Addressing Concerns about Electrical Vehicle Batteries. Coltura. Available online: https://www.coltura.org/evbatteries (accessed on 8 July 2022).
12. Gravitas. The Dark Side of Electric Vehicles. Gravitas Plus. Available online: https://www.youtube.com/watch?v=RFHvq-8np1o&t=1s (accessed on 8 July 2022).
13. Banza Lubaba Nkulu, C.; Casas, L.; Haufroid, V. Sustainability of artisanal mining of cobalt in DR Congo. *Nat. Sustain.* **2018**, *1*, 495–504. [CrossRef] [PubMed]
14. USEPA. An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling, Office of Resource Conservation and Recovery, EPA 530-R-21-002. 2021. Available online: https://www.epa.gov/system/files/documents/2021-08/lithium-ion-battery-report-update-7.01_508.pdf (accessed on 8 July 2022).
15. Baum, Z.J.; Robert EBird, R.E.; Yu, X.; Ma, J. Lithium-Ion Battery Recycling–Overview of Techniques and Trends. *ACS Energy Lett.* **2022**, *7*, 712–719. Available online: https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.1c02602 (accessed on 8 July 2022). [CrossRef]
16. Chen, X.; Zhou, T. Hydrometallurgical process for the recovery of metal values from spent lithium-ion batteries in citric acid media. *Waste Manag. Res.* **2014**, *32*, 1083–1093. Available online: https://pubmed.ncbi.nlm.nih.gov/25378255/ (accessed on 8 July 2022). [CrossRef] [PubMed]
17. SciTechDaily. Breakthrough Research Makes Recycling Lithium-Ion Batteries More Economical. SciTechDaily White Paper. Available online: https://scitechdaily.com/breakthrough-research-makes-recycling-lithium-ion-batteries-more-economical (accessed on 8 July 2022).
18. Shi, Y.; Chen, G.; Liu, F.; Yue, X.; Chen, Z. Resolving the Compositional and Structural Defects of Degraded $LiNi_xCoyMnzO_2$ Particles to Directly Regenerate High-Performance Lithium-Ion Battery Cathodes. *ACS Energy Lett.* **2018**, *3*, 1683–1692. [CrossRef]
19. Yang, Y.; Xu, R.; Zhang, K.; Lee, S.; Mu, L.; Liu, P.; Waters, C.K.; Spence, S.; Xu, Z.; Wei, C.; et al. Quantification of Heterogeneous Degradation in Li-Ion Batteries. *Adv. Energy Mater.* **2019**, *9*, 1900454. [CrossRef]
20. Jiang, G.; Zhang, Y.; Meng, Q.; Zhang, Y.; Dong, P.; Zhang, M.; Yang, X. Direct Regeneration $_{0.3}$ of $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ Cathode from Spent Lithium-Ion Batteries by the Molten Salts Method. *ACS Sustain. Chem. Eng.* **2020**, *8*, 18138–18147. [CrossRef]
21. Neumann, J.; Petranikova, M.; Meeus, M.; Gamarra, J.D.; Younesi, R.; Winter, M.; Nowak, S. Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling. *Adv. Energy Mater.* **2022**, *12*, 2102917. [CrossRef]
22. Folayan, T.-O.; Lipson, A.L.; Durham, J.L.; Pinegar, H.; Liu, D.; Pan, L. Direct Recycling of Blended Cathode Materials by Froth Flotation. *Energy Technol.* **2021**, *9*, 2100468. [CrossRef]
23. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **2019**, *575*, 75–86. [CrossRef] [PubMed]
24. Kallitsis, E.; Lander, L.; Edge, J.; Bravo Diaz, L.; Brown, A.; Kelsall, G.; Offer, G.; Korre, A. *Safe and Sustainable Lithium-Ion Batteries*; Imperial College London: London, UK, 2022. [CrossRef]
25. Chen, M.; Ma, X.; Chen, B.; Arsenault, R.; Karlson, P.; Simon, N.; Wang, Y. Perspective Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries. *Joule* **2019**, *3*, 2622–2646. [CrossRef]
26. CAEPA. Lithium-Ion Car Battery Recycling Advisory Group Final Report. California EPA. Available online: https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf (accessed on 8 July 2022).
27. API. Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries. American Petroleum Institute. Available online: https://www.api.org/~{}/media/Files/Oil-andNaturalGas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf (accessed on 8 July 2022).
28. Ioakimidis, C.S.; Murillo-Marrodán, A.; Bagheri, A.; Thomas, D.; Genikomsakis, K.N. Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios. *Sustainability* **2019**, *11*, 2527. Available online: https://www.mdpi.com/2071-1050/11/9/2527 (accessed on 8 July 2022). [CrossRef]
29. Mobilityhouse. World's Largest 2nd-use Battery Storage Is Starting Up. Mobilityhouse Press Release. Available online: https://www.mobilityhouse.com/int_en/magazine/press-releases/worlds-largest-2nd-use-battery-storage-is-starting-up.html (accessed on 8 July 2022).
30. ADB. Handbook on Battery Storage Systems. Asian Development Bank. Available online: https://www.adb.org/sites/default/files/publication/479891/handbook-battery-energy-storage-system.pdf (accessed on 8 July 2022).
31. ESS Inc. Clean, Long-Duration Energy Storage: The Right Solution, The Right Time. Energy Storage Systems Inc. Available online: https://essinc.com/wp-content/uploads/2021/05/ESS_OnePager_FINAL_5-10-21_lowres.pdf (accessed on 8 July 2022).

32. Service, R. New Type of Flow Battery Can Store 10 Times the Energy of the Next Best Device. Science.org. Available online: https://www.science.org/content/article/new-type-flow-battery-can-store-10-times-energy-next-best-device (accessed on 8 July 2022).
33. Zhu, J.; Mathews, I.; Ren, D.; Li, W.; Cogswell, D.; Xing, B.; Sedlatschek, T.; Nithin, S.; Kantareddy, R.; Yi, M.; et al. End-of-life or second-life options for retired electric vehicle batteries. *Cell Rep. Phys. Sci.* **2021**, *2*, 100537. Available online: https://www.sciencedirect.com/science/article/pii/S2666386421002484 (accessed on 8 July 2022). [CrossRef]
34. Arabkoohsar, A. Chapter One—Classification of energy storage systems. In *Mechanical Energy Storage Technologies*; Academic Press: Cambridge, MA, USA, 2021. [CrossRef]
35. ESA. End-of-Life Management of Lithium-ion Energy Storage Systems. Energy Storage Association. Available online: https://energystorage.org/wp/wp-content/uploads/2020/04/ESA-End-of-Life-White-Paper-CRI.pdf (accessed on 8 July 2022).
36. 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]
37. Stenarecycling. EU Battery Regulation Make New Demands on Industry. Stenarecycling. Available online: https://www.stenarecycling.com/events/future-of-battery-recycling/eu-battery-regulations-make-new-demands-on-industry-3/ (accessed on 8 July 2022).
38. GBA. The Global Battery Alliance Battery Passport: Giving an Identity to the EV's most Important Component. Global Battery AccdeptedAlliance. Available online: https://www.globalbattery.org/media/publications/wef-gba-battery-passport-overview-2021.pdf (accessed on 8 July 2022).
39. Wardsauto. U.S. EU Rules as EV Batteries Reach End of Road. Wardsauto. Available online: https://www.wardsauto.com/powertrain/us-eu-rules-ev-batteries-reach-end-road (accessed on 8 July 2022).
40. UCSUSA. Electric Vehicle Batteries: Addressing Questions about Critical Materials and Recycling, Union of Concerned Scientist of USA. Available online: https://www.ucsusa.org/resources/ev-battery-recycling (accessed on 8 July 2022).