Assessment of the Environmental Impact of Used Lithium-Ion Batteries

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Abstract—There is a growing demand for lithium-ion batteries (LIBs) to support the implementation of renewable energy through electricity transmission and auxiliary energy storage systems. This increased demand necessitates a simultaneous rise in production, resulting in a significant volume of spent LIBs. The ever-increasing battery waste must be managed appropriately. Currently, there are no universal or unified standards for LIB waste disposal globally.

This review identifies, categorizes, and highlights the environmental impacts, sources, and pollution pathways associated with spent LIBs. It emphasizes the shortcomings of disposal practices and discusses the associated risks. The toxicity of battery materials poses a direct threat to organisms at various trophic levels as well as to human health. Identified pollution pathways include leaching, disintegration, and degradation of batteries, while extreme events such as fires and explosions are also significant. Finally, the article discusses key knowledge gaps for future assessments. The current research provides a comprehensive review of the threats and risks that must be managed to ensure the design and implementation of safe disposal and recycling options for spent LIBs.

Keywords—Lithium-ion batteries, Environment, Recycling, Pollution, Landfill, Management of resources

I. Introduction

Lithium-ion batteries (LIBs) are integral to many facets of everyday life, ranging from compact electronic gadgets to electric vehicles (EVs) and battery energy storage systems (BESS). LIBs are considered essential for facilitating the widespread use of renewable energy sources since these sources necessitate BESS to manage their power supply variability, ensuring a dependable operation of the electricity grid. The use of LIBs in electric propulsion has sparked a transformation in the automotive sector, which is driven by the goal of decarbonizing transportation and alleviating local air pollution. In 2009, around 25.6 GWh (approximately 134000 tons) of lithium-ion battery (LIB) energy storage capacity was introduced globally, while in 2019, this figure rose to about 218 GWh (more than 1.2 million tons). Projections indicate that by 2030, over 2500 GWh (exceeding 12.7 million tons) will be launched on the market, leading to a significant amount of waste generated from used LIBs [1].

On one side, the rising number of lithium-ion batteries (LIBs) raises worries about the availability of certain critical metals and their erratic short-term price fluctuations, which could impact the sustainable supply of these energy storage devices [2]. Additionally, there are ethical and environmental issues associated with the extraction of some metals used in LIBs [3]. On the other side, this increase in battery demand will necessitate a corresponding rise in production, leading to a significant number of LIBs eventually reaching the end of their life (EoL). Consequently, this will result in a growing amount of battery waste that must be managed appropriately [4]. Many batteries, unfortunately, find their way into landfills or are incinerated, mainly because of insufficient standards, poor enforcement of regulations, or the lack of effective national programs for battery collection and recycling [5]. Consequently, human health and environmental quality may be endangered, as various pollutants, including heavy metals and hydrofluoric acid (HF), can be released when batteries are improperly disposed of.

The primary objective of this research is to present a current overview of the environmental effects and risks posed by spent batteries. This document examines and evaluates the fate, disposal methods, and potential sources and pathways of pollution resulting from spent lithium-ion batteries (LIBs). Although the significance of this topic is clear, there is a severe lack of data on the environmental consequences of end-of-life (EoL) LIBs; therefore, this study seeks to identify the potential ecological impacts related to battery EoL. Manufacturers, waste management companies, recycling organizations, and public stakeholders urgently need to comprehend this issue, as improper disposal practices, insufficient data, or failure to accurately identify hazards could significantly raise the occurrence of incidents, fires, and potentially life-threatening accidents. The potential pathways for emissions and pollution, such as air, water, and land, are examined throughout this research. We have also acknowledged the potential risks to human health and ecosystem integrity resulting from various battery handling and disposal methods.

II. DISCARDING USED BATTERIES

The management of used LIBs involves various methods such as reuse, recycling, disposal in landfills, processing, or unfortunately, illegal disposal. Local disposal methods are influenced by national laws and regulations, recycling capabilities, collection systems, consumer habits, and the battery retail landscape. Clearly, distinct strategies are necessary for handling small batteries as opposed to larger ones.

Small LIBs are returned by customers either through designated battery drop-off locations (for LIBs that can be easily detached from devices) or taken to waste electrical and electronic equipment (WEEE) facilities if the user is unable to remove them from the devices.

Large lithium-ion batteries (LIBs) are generally moved by specialized services once they are no longer in electric vehicles (EVs) [5]; however, their condition is often unknown. If they have internal damage, they may enter a state of slow thermal runaway and go unnoticed for an extended period, potentially leading to them catching fire or emitting gases and solvent droplets, referred to as ''white vapor'', which consist of harmful and potentially explosive gases. [6] - [10]. These incidents can occur during transportation, storage, recycling, or disposal in a landfill.

II.1 Recycling

Material recovery is an effective strategy for reducing reliance on external raw mining or safeguarding the nation's limited resources. For example, by 2050, it is anticipated that up to 60% of lithium demand for lithium-ion batteries (LIBs) in China could be satisfied through recycling. Presently, China is the foremost producer and consumer of LIBs, with the recycling of used LIBs beginning only recently. Although there are approximately 14 legislative measures aimed at managing emissions from all types of battery waste, effective regulation of spent LIBs remains in its early stages. In the United States, the oversight and management of LIBs are inconsistent, reflecting the federal structure, where some federal regulations, like the 1996 Mercury-Containing and Rechargeable Battery Management Act, provide guidelines for battery disposal and set standards. Nonetheless, the overall situation comprises a disjointed framework of state-specific regulations that vary significantly in maturity and effectiveness. In the European Union, new legislation aimed at overseeing the sourcing of raw materials, disposal, and recycling of LIBs is set to take effect in 2022.

Recycling methods

Material recovery from end-of-life lithium-ion batteries (LIBs) is currently achieved through one of three primary methods: pyrometallurgy, hydrometallurgy, and direct recycling [11], [12]. Pyrometallurgy employs a high-temperature smelting process, typically involving combustion and subsequent separation, to create a mixed metal alloy containing cobalt, copper, iron, and nickel. This is a well-established method that is frequently used for both small and large lithium-ion batteries, particularly those rich in cobalt. Generally, this technique does not necessitate pre-sorting of the battery types; however, the resulting alloy needs additional processing. Hydrometallurgy retrieves the desired metals from cathode materials through leaching in either an acidic or basic aqueous solution. [13] . This method requires further steps such as concentration and purification afterward. While this process can recover almost all components of LIBs with high purity,[14]. the separation of metals from one another demands further purification steps; moreover, unlike pyrometallurgy, sorting is essential. Lastly, direct recycling pertains to the immediate reuse of the cathode and/or anode materials from the spent LIBs following reconditioning. Although this method is conceptually promising as it allows for the straightforward recovery and reuse of most battery components [15], [16], [17]. without extensive processing, it remains an underdeveloped technology. Additionally, there are alternative technologies being explored, such as plasma smelting [18], bioleaching [19], and redox targeting-based material recycling [20].

In contrast, hydrometallurgy generates significantly lower greenhouse gas emissions, but it requires additional wastewater treatment to prevent pollution in receiving waters, such as acid contamination. Reports indicate that hydrometallurgical recycling processes impose environmental risks related to freshwater and terrestrial acidification [21]. Mohr et al. (2020) conducted a comparison of the environmental impacts associated with recycling various battery chemistries (i.e., NMC, NCA, LFP, and solid-state) using a standard pyrometallurgical method, a typical hydrometallurgical process, and an advanced hydrometallurgical technique (which recovers graphite and electrolyte) [22]. The findings revealed that advanced hydrometallurgical processes tend to be the most effective in terms of global warming impact, owing to the extra recovery of graphite and electrolyte, whereas the pyrometallurgical approach ranks lowest due to its high energy requirements and insufficient lithium recovery. The authors also recommended that a chemistry-specific strategy for recycling be considered, as certain processes may lead to adverse environmental effects when treating specific chemistries; for instance, hydrometallurgical recycling of LFP and sodium-ion batteries may contribute further to abiotic resource depletion potential, or the pyrometallurgical recycling of LFP cells could heighten global warming impact. Since direct recycling is still in the initial phases of development, there is no real-world data available on the potential pollution it may cause. According to Dun et al. (2015), employing a direct recycling process for NMC, LCO, LFP, and LMO batteries could greatly reduce greenhouse gas and sulfur oxide emissions (associated with battery production), thereby mitigating the global warming and acidification potential throughout the entire battery life cycle [23]. It is important to note that when evaluating the environmental impacts of a specific recycling process, the net environmental impact is generally assessed by calculating the difference between emitted and avoided emissions (recycling benefits). The cycling process itself may negatively affect the environment in a particular impact category, while the benefits from recycled materials (the environmental impacts avoided by reintroducing recovered materials to the market) could offset these adverse effects, resulting in a net positive environmental outcome. It is important to recognize that the environmental impacts of various recycling processes can differ depending on the type of cell chemistry being processed, the emission reduction technologies used, the efficiency of recycling, and the quality of the recovered materials.

II. 2. Landfill

Disposal of solid waste [24] primarily occurs through landfilling, with municipal waste deposition rates of 53% in the USA, 79% in China, and 94% in Malaysia [25]. Approximately 4% of this waste consists of electronic waste (e-waste), which frequently contains batteries [26]. Given the low rates of global recovery, it is evident that a significant amount of e-waste, particularly those with small lithium-ion batteries (LIBs), ends up in landfills rather than being recovered [27]. This situation applies not only to many developing nations but also to developed countries, largely due to insufficient regulations and inadequate recycling infrastructure. Therefore, at least in the short term, it is almost certain that LIBs, especially from smaller portable devices, will remain buried. Currently, because of the relatively small number of electric vehicles (EVs), large LIBs are typically recycled [28]. However, as the volume increases and infrastructure remains lacking, even high-capacity batteries may face disposal in landfills or temporary storage. Nevertheless, in the long run, these batteries are more likely to be recovered than disposed of, as discarding them would squander a significant resource of valuable materials. Landfills can act as either a source or a sink for pollution, leading to adverse effects on nearby communities. [29]

The principal sources of emissions from landfills include surface dust, landfill gases (like biogas), leachate, and fires [30], [31]. The degree of pollution resulting from a site is influenced by its location, waste composition, age, and geo-climatic factors [32]. However, in the future, landfills may transform into areas for valuable resources through urban mining, serving as a repository for rare and essential metals that can be retrieved without the need for traditional mining.

II.3 Illegal disposal and processing

Whenever there is an opportunity for profit, there will be efforts to circumvent official business channels. As recycling lithium-ion batteries (LIBs) can be somewhat profitable, there is a significant likelihood of illegal processing occurring, similar to what has happened with waste electronic devices. Such illicit activities can lead to environmental contamination around processing sites, unsafe working conditions for employees, and ultimately a decline in their health and quality of life. Illegal disposal may take place if the costs of recycling or official landfilling are deemed "too expensive" for certain businesses. Illegal dumpsites can arise in highly unsuitable locations, resulting in serious pollution, unforeseen fires, and substantial additional expenses for local residents and councils regarding utilization and cleanup of the area. Unanticipated incidents (e.g., fires) may happen even months post-disposal, complicating the process of identifying those responsible.

It is inevitable that LIBs will be subject to illegal recycling and disposal [33]. Furthermore, the burden of these unlawful activities will predominantly fall on emerging economies, where labor costs are lower, and there is a lack of recycling infrastructure along with stricter environmental regulations found in developed nations. A clear example of this exploitation is the transfer of e-waste from affluent and developed countries to poorer, developing ones [34], [35]. This is also evident in the data: for instance, two-thirds of global e-waste collected in 2014 was exported, with the troubling fact that half of it was routed through illegal channels [36]. This resulted in over 3 million tonnes of e-waste being sent outside of regulated frameworks. Data from 2019 indicates that 82.6% of global e-waste flows were neither formally collected, properly managed, nor adequately documented [37]. The EU generates approximately 44.3 million tonnes of e-waste each year; however, only 0.6 million tonnes are reported to actually reach landfills, while the remainder is either dumped, traded, informally exported, or recycled in environmentally damaging ways. [38]. Therefore, there is no assurance that exported end-of-life LIBs will be recycled or processed in a regulated, safe, or environmentally friendly manner[39].

II.4 Incidents involving LIBs

Incidents involving lithium-ion batteries (LIBs) mainly highlight concerns related to fires and the emission of toxic gases. Apart from the dangers these hazards pose to emergency responders and bystanders at situations such as road traffic collisions, there is also an extensive range of environmental repercussions from such fires.

The occasionally explosive failures of LIBs arise from various forms of misuse, which can include heat exposure, physical penetration, blunt force impact, or overcharging, with literature documenting instances across land, sea, and air [40], [41]. Spontaneous fires involving LIBs have also been noted, especially in relation to electric vehicles; the precise causes remain largely unidentified, but issues during manufacturing or inadequate design have frequently been cited. A growing and somewhat concerning trend is the occurrence of fires and explosions within large lithium-ion battery energy storage systems (LIBESS). The first recorded incident took place in Arizona in 2012, involving a newly installed 1.5 MW LIBESS owned by Arizona Public Services [42]. Multiple design deficiencies were revealed after the incident, including insufficient ventilation and poor monitoring systems, which were reportedly meant to be rectified [43] when a second LIBESS owned by APS exploded in April 2019, resulting in injuries to four first responders, two of whom were seriously hurt. This incident is now thought to have resulted from a vapor cloud explosion [44], [45].

LIBs are increasingly being utilized in marine transport. They can serve as a propulsion mechanism for vessels such as ferries or even submarines, [46] as well as for energy recovery and hybrid systems. The primary benefits typically include reduced weight and enhanced efficiency compared to traditional systems like lead-acid batteries. Similar to electric vehicles and battery energy storage systems, there exists a risk of faults, incidents, fires, and subsequent contamination of aquatic ecosystems. One such occurrence involved a fire and subsequent gas explosion on a diesel-electric ferry in Norway on October 10th—the fire was detected during the voyage, but the ferry managed to return to harbor using its power, allowing for the safe evacuation of all passengers. However, overnight, a significant gas explosion occurred in the battery room, causing considerable damage. It was reported that twelve firefighters were hospitalized due to their exposure to hazardous gases linked to the burning batteries.

Performance Improvement Strategies for Lithium-Ion Batteries

1. Optimizing Recycling Processes

A crucial aspect of enhancing lithium-ion battery performance is refining the recycling method. Existing recycling techniques, such as hydrometallurgy and pyrometallurgy, present challenges in terms of cost, material recovery efficiency, and ecological consequences. Shifting to direct recycling approaches, which facilitate the reuse of cathode and anode components with minimal processing, could greatly boost efficiency while decreasing waste. Establishing standardized recycling practices worldwide would help achieve higher recovery rates for valuable resources like lithium, cobalt, and nickel.

2. Improvements in Safety

A major concern with lithium-ion batteries is the potential for thermal runaway, leading to fires or explosions. Battery management systems (BMS) can be advanced by including real-time monitoring sensors that identify early indications of failure, such as excessive heat or internal short circuits. Moreover, utilizing non-flammable electrolytes or transitioning to solid-state battery technology could substantially lower fire risks and enhance overall safety.

3. Enhancing Energy Density and Longevity

Boosting the energy density of lithium-ion batteries while ensuring safety is vital for their ongoing development. Innovations in anode materials, specifically silicon-based anodes, have demonstrated promise for increasing capacity without sacrificing durability. Likewise, advancements in electrolyte formulations and separator materials can improve cycle life and battery stability, making them more appropriate for long-term use.

4. Effective End-of-Life Strategies

A comprehensive disposal and reuse plan for used lithium-ion batteries can help avoid environmental contamination and enhance resource recovery. Promoting second-life uses—where electric vehicle batteries are repurposed as stationary energy storage solutions—can prolong their utility before recycling. Implementing stricter regulations against battery landfill disposal and incentivizing proper collection and processing systems can lead to better environmental results.

5. Mitigating Environmental Impact

Reducing the carbon footprint associated with battery production and disposal is critical for sustainable progress. Utilizing renewable energy sources in manufacturing facilities, streamlining supply chain logistics, and designing batteries with modularity for easier disassembly and recycling can enhance battery lifecycle sustainability. Furthermore, creating safer and more efficient disposal methods, such as immobilizing toxic substances prior to landfilling, can prevent hazardous leakage into soil and water sources.

By concentrating on these improvement areas, lithium-ion batteries can evolve to be more efficient, safer, and environmentally sustainable, solidifying their role in the shift towards a sustainable energy future.

III. Conclusion

The continuous advancement of lithium-ion battery technology is essential for enhancing efficiency, safety, and sustainability. By improving recycling processes, optimizing material recovery, and developing safer battery chemistries, we can reduce environmental impact while maximizing resource utilization. Implementing robust battery management systems and exploring second-life applications will further extend battery lifespan and minimize waste. Additionally, fostering innovation in energy density and alternative materials will ensure that lithium-ion batteries remain a cornerstone of energy storage solutions. A comprehensive approach that includes regulatory support, technological innovation, and sustainable practices will be key to shaping a more efficient and eco-friendly future for lithium-ion batteries.

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