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REVIEW ARTICLE

Recycling of Li-Ion and Lead Acid Batteries: A Review

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Abstract | The rapid shift toward producing and using clean energy to replace fossil fuels has increased the need for batteries. Batteries have become an integral part in energy storage applications due to their increased demand in electric vehicles, consumer electronics, and grid scale storage. As the demand and usage of batteries increase, it is desired to study their recyclability to reduce the environmental impact. Among the available batteries, lithium ion (Li-ion) and lead acid (LA) batteries have the dominant market share. This review paper focuses on the need to adopt a circular economy with effective recycling of batteries. Furthermore, the state-of-the-art processes to recycle batteries and challenges faced by companies to recycle Li-ion and LA batteries are discussed. It is found that the recyclability of Li-ion batteries is < 1% and the process is still not efficient to recover Li for reuse in battery applications. LA batteries are now recycled with more than 99% efficiency in the USA and EU because of factors such as separation at the source, availability of methods to economically recover materials and regulations supporting recycling. Novel recycling techniques are being developed for effective recycling of Li-ion batteries.

1 Introduction

The global power generation from renewable sources has increased by about 4.5 times during the decade 2010–2020[1]. Currently, hydropower, solar and wind are the major renewable power sources[2–4]. The International Renewable Energy Agency (IRENA), an intergovernmental organization, has reported that producing energy from renewable sources has become cheaper than producing energy from fossil fuels[1,2]. The growth of solar and wind energy plants in the USA and investment into renewable energy have not been impeded by the global pandemic[5]. Deployment of energy storage technologies is critical to deal with the intermittency of the energy production in solar and wind power plants[6]. The advances made in the battery technologies have contributed toward efficient energy storage in grid-scale applications. Battery technologies have also contributed to rapid growth of electric vehicles, which has helped in further reduction in the use of fossil fuels[7–9]. Such large-scale applications of batteries require analysis of the impact of batteries on the environment, assessing the current state of the art in their recyclability, and finding sustainable methods to reduce their environmental impact[10].

The total battery market size was estimated to be US $108.4 billion in 2019 and it is expected to grow by 14.1% from 2020 to 2027[11]. The lead acid (LA) batteries account for the highest market share of 29% as shown in Fig. 1. The global LA battery market was estimated to be about $59 billion during 2018[12]. Although the use of lithium-ion (Li-ion) batteries is rapidly increasing, especially in electrical vehicles and electronic devices, the overall growth of the energy storage device sector is sustaining the LA battery market in terms of volume. The LA and Li-ion batteries have high market share because of their high energy capacity, low maintenance, and higher life cycle compared to

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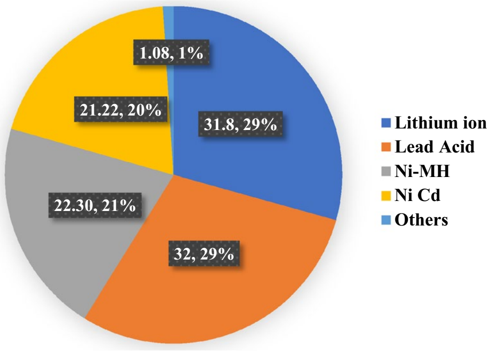


Figure 1: Estimated market share of different batteries in the year 2019 (US$ in billions, % market share).

many other batteries[13–18]. Ni-metal hydride and Ni–Cd batteries also have sizable market shares. It is expected that the market share of Li-ion batteries will eventually surpass the LA batteries by 2027[11]. Acknowledging this rising trend, the aim of this work is to review the recyclability of Li-ion and LA batteries.

The rest of the article is structured as follows: in Sect. 2, a set of performance indicators of typical LA and Li-ion battery technologies are tabulated. In Sect. 3, the concept of circular economy is introduced in context with the battery technologies and the LA and Li-ion battery technologies are discussed. In Sect. 4, the recycling methods used for LA and Li-ion batteries are described, and in Sect. 5, the novel and prospective recycling techniques for Li-ion batteries are discussed. Finally, Sect. 6 discusses the challenges faced by the current recycling methods.

2 Performance Metrics of LA and Li-Ion Batteries

The global Li-ion battery market is projected to reach \$129.3 billion by 2027[19]. The key applications contributing to the Li-ion market share include electric vehicles, smartphones, laptops and other electronic devices[14] due to higher gravimetric energy densities and volumetric densities[20,21]. LA batteries possess a large power-to-weight ratio due to which they are the primary energy sources in combustion engine automotive, industrial and grid energy storage systems[22–24]. In spite of rapid growth of Li-ion batteries, the LA batteries are predicted to surpass US \$116 billion market share by the end of 2030[25]. The key characteristics of LA and Li-ion batteries are presented in Table 1. Although several sets of Li-ion battery chemistries are available with varying performance characteristics[26,27], Table 1 only includes the performance characteristics of $LiFePO_4$ (LFP) battery chemistry as a typical example, since it has been reported that LFP batteries have been used for a longer duration in the market due to the recent shift to the electric vehicle (EV) automobile industry[28–30]. However, it should be noted that the performance metrics given for both LA batteries and Li-ion batteries in Table 1 are for a general overview and the values can vary depending on the battery chemistry, operating conditions, and application[31–34]. Irrespective of the performance metrics, the hazards related to stacking Li-ion batteries for large-scale applications and very low recycling rate need immediate attention for them to surpass LA batteries.

An area of overlap in the applications between the LA and Li-ion batteries is the renewable

Table 1: Performance metrics of LA and Li-ion batteries.

Factor	LA batteries	Li-ion batteries
Depth of discharge	~30–50%[31]	~80–95%*[31]
Cycle life	~500–1000 cycles[31]	~4000–5000 cycles*[31]
Efficiency	~78–85%[31]	~92–98%*[31,32]
Capacity loss at high loads	~40%	0
Charging	Slower	Faster
Size and weight	Bulky	Compact
Wasted energy	~15%	0
performance at 1C current under harsh temperatures	~70% capacity @40 °C ~30% capacity @– 20 °C[31]	~98% capacity @40 °C ~80% capacity @– 20 °C*[31]
Battery and installation costs	Lower	Higher
Recycling rates	~99%[33,34]	~5%[33,34]

*Li-ion batteries with LFP battery chemistry

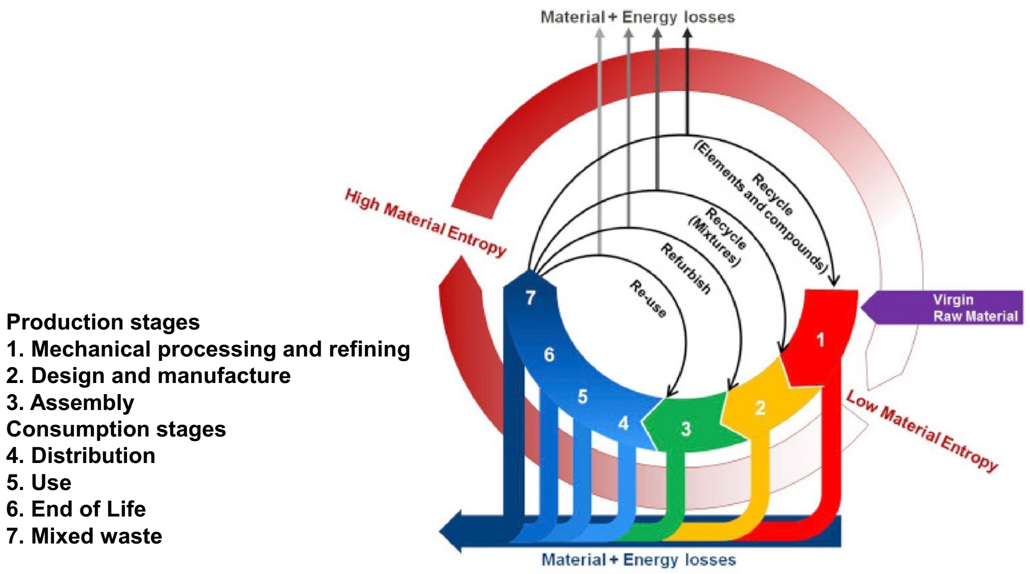


Figure 2: Circular economy model for material-centric perspective[42]. The figure shows that the reuse has the lowest energy penalty, while recovering elements is beneficial but has the highest energy penalty. Reproduced with permission.

energy storage systems. Over the past decade, the prices for solar panels and wind farms have decreased significantly leading to installation of hundreds of gigawatts of new renewable energy generation plants. Installed wind power capacity grew from 17,000 MW in 2000 to 563,000 MW in 2018 and solar power grew from a mere 1250 MW in 2000 to 485,000 MW in 2018[35,36]. However, much of this energy needs to be stored to make it available on demand. Though the price of Li-ion batteries is dropping, they are still considered too expensive for such applications[37]. In addition, Li-ion batteries are prone to fire hazards in large stacks and their ability to hold the charge fades over time[38].

3 Circular Economy for Batteries

Considerable ongoing efforts are focused on recycling of batteries[39]. Disposal of batteries in landfills can cause groundwater contamination due to leaching of metals. Incineration can release metals such as mercury into air and the resulting ash that contains cadmium and lead can contaminate soil and groundwater[40]. While recycling is desired and has been efficiently implemented for LA batteries, the technology is not economically viable for many other batteries. Several frameworks have been proposed to tackle the issue of battery disposal. One such framework proposed by the European Union (EU) is known as the "Waste from Electrical and Electronic Equipment (WEEE)" that provides guidelines for sustainable production and consumption and addresses the growing environmental risks due to the discarded electronic waste known to have some hazardous materials[41]. The WEEE framework is based on the concept of circular economy. A generic scheme of circular economy with material-centric perspective is shown in Fig. 2[42]. Businesses develop their own supply chain model focusing on recovery or recycling the resources used to create their products. A critical aspect of the circular economy is the economical recyclability. Studies have shown that separation of waste in different streams at the source can significantly reduce the cost of recovery. As an example, 97% of plastic bottles are recycled in Norway due to a large retail network for used bottle collection. Bottles disposed of in general garbage are very expensive to recover. Recycling of LA batteries has demonstrated that batteries are a viable product for circular economy. However, recycling of Li-ion batteries is not economically feasible due to a combination of technical challenges such as the intricate design which requires a lot of manual labor to disassemble the battery and presence of hazardous materials. A combination of technical advancements[43], development of standards and regulatory guidelines can advance the recycling of these newer batteries.

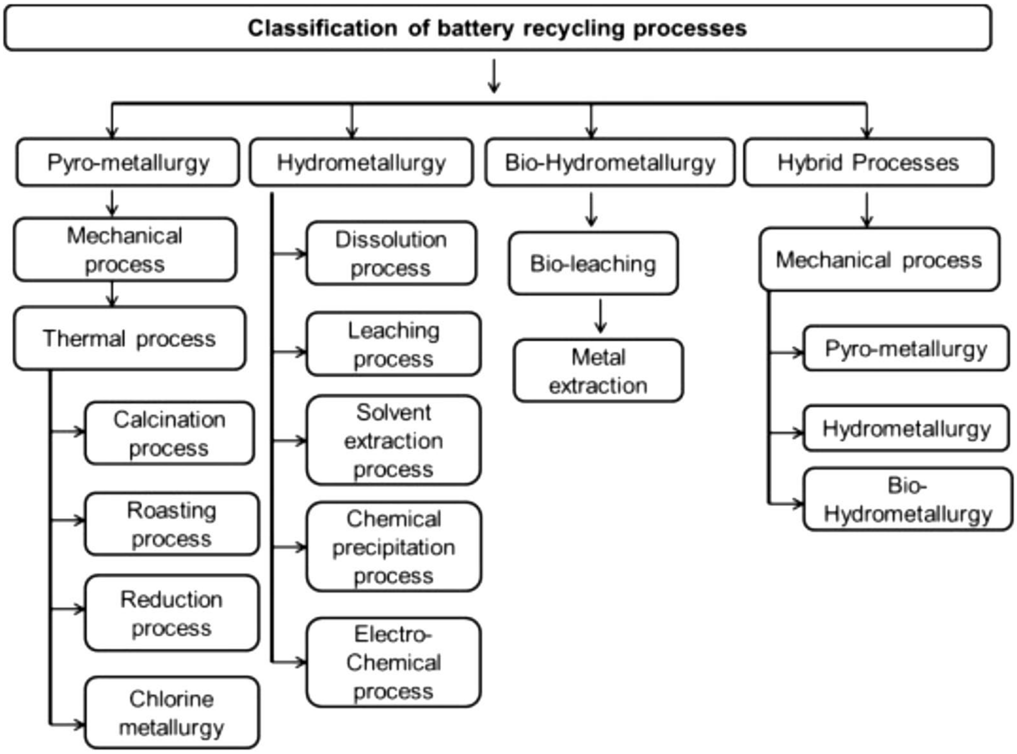


Figure 3: Classification of various recycling processes[51]. Reproduced with permission.

3.1 Lead Acid (LA) Batteries

The main lead ore is known as galena[44]. Lead is commonly found in granitic rocks, rhyolite, and black shale, among others. World lead resources total more than 2 billion tons in Australia, China, Ireland, Mexico, Peru, Portugal, Russia, and the USA (Alaska)[45]. But it has been reported that about 50% of refined lead produced worldwide is from recycled material. Secondary lead production requires less energy than primary extraction[46]. The LA batteries accounted for about 92% of the US lead consumption in 2020[45]. LA batteries are composed of a positive plate consisting of lead dioxide (PbO_2), a negative plate composed of lead (Pb) and an electrolyte which is diluted H_2SO_4 solution. LA batteries were primarily used for starting–lighting–ignition (SLI) applications in automobiles and as industrial-type batteries for standby power for computer and telecommunications networks. LA batteries are constructed in two types—flooded or sealed. Flooded (or wet) LA batteries have electrodes or plates immersed in an electrolyte. In a sealed LA battery, also known as valve-regulated lead acid (VRLA) battery, the electrolyte is immobilized.

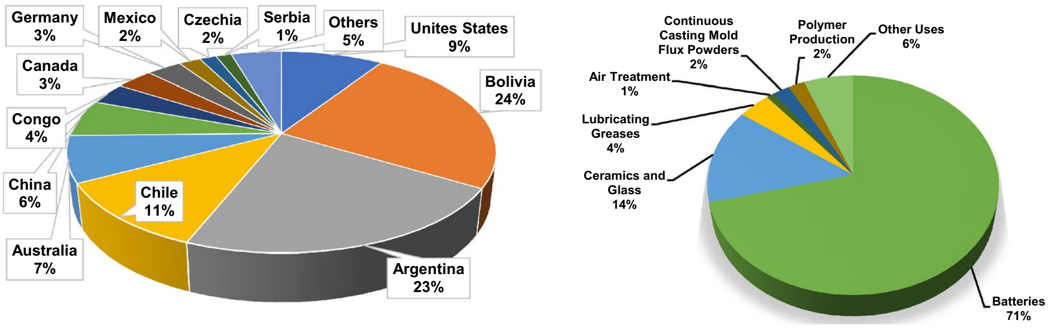
The LA batteries are highly recycled. Studies by the Battery Council International showed that the recycling of LA batteries increased from 95% in 2010[45,47] to 99% in 2019[48,49]. Pyrometallurgy and hydrometallurgy methods are applied for recycling, in association with pretreatment of spent LA batteries. A range of hydrometallurgy-based technologies are being developed and adopted due to raising concerns from environmental legislations[44,50].

The classification of various recycling methods is shown in Fig. 3 [51]. Recycling process of Li-ion and LA batteries is complex, requiring a multistage process chain. Current recycling processes for end of life (EOL) batteries can be divided into four process steps—preparation, pretreatment, and pyrometallurgy followed by hydrometallurgy. These steps are combined in different sequences to get the best possible output[52,53]. A typical recycling loop is shown in Fig. 4[54].

3.2 Lithium in Li-Ion Batteries

Lithium is a highly reactive and flammable material; therefore, it is found in nature as a compound[55,56]. The global extraction of lithium is mainly from four compounds—lithium carbonate[57], lithium hydroxide, lithium chloride, and butyl lithium [51]. Commercial concentrations

Figure 4: A typical recycling loop for spent batteries[54]. Reproduced with permission.



(a) (b)

Figure 5: **a** Production of Li from various countries and **b** usage of Li in various applications. Data taken and replotted from[45].

of lithium are found in brines, minerals, and clays in various parts of the world. Brine is the major resource (59%) for lithium occurrence[45,58]. The world Li reserves have been estimated to be 86 million metric tons as of 2020, as per the geographical distribution shown in Fig. 5a[45]. Figure 5b shows that lithium is predominantly used in batteries and its consumption has increased significantly in recent years because rechargeable Li-ion batteries are used extensively in portable electronic devices, electric tools, and electric vehicles.

Li-ion battery consists of cathode, anode, electrolyte, and separator that are housed in a protective metal casing, a design that is similar to LA batteries. Li metal, Li-alloy or material adsorbing

Table 2: Li-ion battery constructive components and materials[61].

Battery Component	%w/w	Most used material
Case	~25%	Steel/plastics
Cathode	~27%	$LiCoO_2$, $LiNi_xMn_yCo_zO_2$, $LiMn_2O_4$, $LiNiO_2$, $LiFePO_4$
Anode	~17%	Graphite/$Li_4Ti_5O_{12}$
Copper and aluminum foils and current collectors	~13%	Cu/Al
Electrolyte	~10%	Solution of $LiPF_6$, $LiBF_4$, $LiClO_4$, and $LiSO_2$ dissolved in propylene carbonate, ethylene carbonate, or dimethyl sulfoxide
Separator	~4%	Microporous polypropylene
Binder	~4%	Polivinylidene difluoride (PVDF)

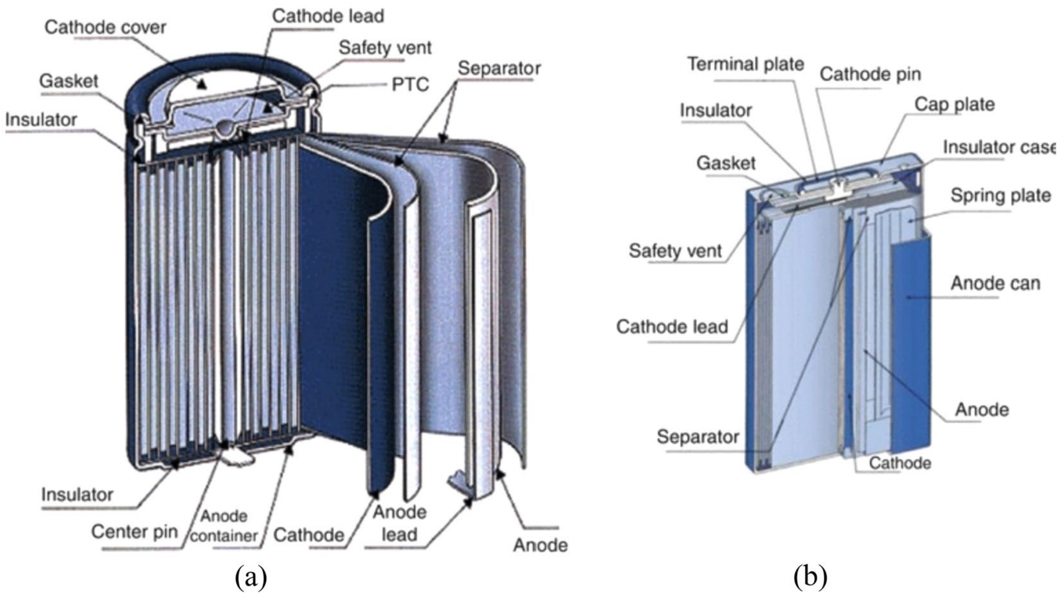


Figure 6: Constructional design of Li-ion cells: **a** cylindrical and **b** pouch designs[62]. Reproduced with permission.

Li-ions is used for its negative active material electrode. One of the negative active materials used is graphite due to its ability to absorb Li-ions[59,60]. The Li-ion batteries are classified as primary and secondary batteries depending on the battery chemistry. The primary batteries are non-rechargeable and consist of metallic Li[58]. The secondary batteries have chemistry that allows reversible reactions making them capable of recharging. The working principle behind the Li-ion batteries is based on the following chemical reaction:

$$LiCo_yO_z + 6C \rightarrow Li_xC_6 + Li_{1-x}Co_yO_z. \tag{1}$$

A typical Li-ion battery consists of metals such as Co, Li, Cu, Al, Fe and Ni, organic chemicals, and plastics. The content of these materials in a typical battery are summarized in Table 2[61]. A schematic of the Li-ion battery is shown in Fig. 6[62], assembled in cylindrical and pouch design. These two designs are the most used battery shapes for the current applications[63].

Most of the current recycling efforts are focused on the recovery of Co, Ni due to their higher prices in the secondary market, or other metals rather than lithium[47,53]. Recovery of Li may become one of the objectives only if the Li prices in the secondary market become attractive. In fact, the battery recycling industry has expressed concerns about the reduction of Co

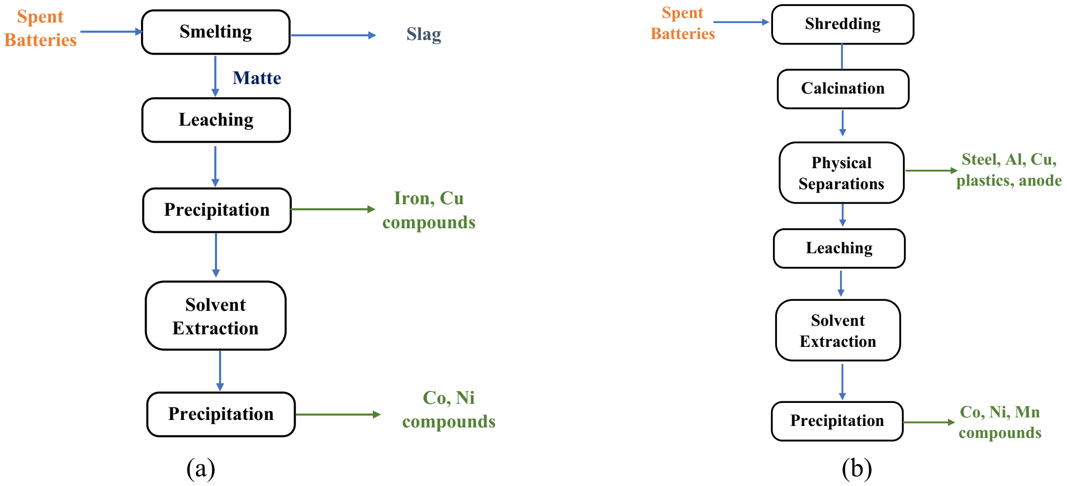


Figure 7: Process diagram for a generic **a** pyrometallurgical and **b** hydrometallurgical recycling process. Solid boxes denote common operations; dashed boxes denote optional unit operations; green denotes products. Data taken and replotted from[76].

use in Li-ion batteries because reduced yields of cobalt could make the recycling processes uneconomical. Because of the evolving chemistry for Li-ion batteries and delay in large-scale deployment of electric vehicles, the recycling industry is finding it challenging to develop profitable recycling pathways[47]. The UN Environment Program (UNEP) status report on recycling rates of metals reported that $<1\%$ of lithium is being recycled. Currently, up to 3% of Li-ion batteries are recycled with the focus of valuable metal recovery[51]. The common recycling processes for Li-ion batteries include (1) hydrometallurgy, (2) pyrometallurgy, and (iii) hybrid processes, where pyrometallurgy is the most widely used approach. Currently, eight companies located in North America are recycling Li-ion batteries to some degree[45].

4 Recycling of Batteries

The processes discussed in this section are common recycling techniques for most battery types[64,65]. LA and Li-ion batteries which are the focus of this work also use the same process[66–71]. The first step in recycling is the preparation and pretreatment process which remove impurities. Following that the concentrate is sent to the pyrometallurgy step. For some applications where refined materials are needed, the product from pyrometallurgy is sent to hydrometallurgy[49,70,72]. Also, due to the inefficiency and environmental concerns[73,] the industry is trying to change from pyrometallurgy to hydrometallurgy[70,71,74]. Each of these processes are explained in the following subsections.

4.1 Preparation and Pretreatment Process

A pretreatment process generally is mechanical or thermal treatment or combination of both where the batteries are dismantled from a large battery pack into a cell or module size, the plastic casing is separated, and the cells are discharged.

As an example, a company Batrec runs a mechanical preprocessing plant for Li-ion batteries[75]. Pretreatment involves steps such as pyrolysis and/or mechanical processing, i.e., material crushing and manual separation. In this step, the cells are crushed under CO_2 gas atmosphere due to which volatile organic electrolyte evaporates and is collected as non-usable condensate. Thereafter, materials separation is done containing the target materials, which forms the feedstock for the following steps.

Similarly, the LA batteries are dismantled and separated into various components. The pastes of lead and lead sulfate are desulfurized using alkaline solution[46] and then various components and the desulfurized paste are sent for pyrometallurgy or hydrometallurgy.

4.2 Pyrometallurgical Recovery

Following the pretreatment process, the residue undergoes extraction and purification in the pyrometallurgical step.

For Li-ion battery in a typical pyrometallurgical process, Li ends up in slag phase which has to be refined and extracted. Due to which it needs purification to supply feed to a hydrometallurgical step for final refining process. This step, Fig. 7a, is necessary since the hydrometallurgy is extremely sensitive to composition fluctuations[76]. Materials such as fluorine, chlorine, graphite, and phosphorus are among those extracted from the residue, which are undesired in the hydrometallurgy, are used for the pyrometallurgy process itself. This process uses a high-temperature furnace to reduce the component metal oxides to an alloy of Co, Cu, Fe, and Ni. It should be noted that Lithium can theoretically be recovered from pyrometallurgy but not economically.

For spent LA batteries with minor crystal structure or compositional changes, it is possible to recover PbO through one step i.e., pyrometallurgy. In this method the lead paste is directly sent to a furnace at temperature higher than 1000 °C for decomposing and melting lead compounds. As lead compounds are reduced to metallic lead at high temperatures any sulfur is often fixed using slags with Fe or soda in the furnace[44]. Pyrometallurgy smelting is still the main technology for spent LA battery recycling.

This process is established commercially for consumer Li-ion and LA batteries. The major drawback for this method is the production of toxic gases, high energy costs and the limited number of materials reclaimed[77,78].

4.3 Hydrometallurgical Metals Reclamation

Following the pyrometallurgy, the final step is refining or extracting high purity material using hydrometallurgy, which is shown in Fig. 7b[76]. This process consists of autoclave, acid leaching, precipitation and filtering of non-noble metals or undesirable elements, followed by solvent extraction and nickel electrowinning, ion exchange and cobalt electrowinning.

For recycling Li-ion batteries this process uses aqueous solutions to leach the desired metals from cathode material. The most common combination of reagents reported is H_2SO_4/H_2O_2[79–81]. As Co in Li-ion battery is bonded strongly to oxygen it is difficult to do acid leaching. In that case it is reported that the use of hydrogen peroxide is more efficient in leaching[77,82]. Further roasting, dissolving, precipitation, filtering, and electro-extraction processes extract copper and other precious metals. The most economically recoverable Li-ion battery materials are cobalt, nickel and copper[83]. This process can be modified to extract lithium in the form of lithium carbonate. In this process[51,] the slag samples are milled to a target particle size (the flue dust does not have to be milled and can be leached directly). After leaching, the solid is filtered out and then washed and analyzed to determine lithium yield.

Similarly, for LA batteries the metallic components are sent for smelting/shredding with coke or a reducing agent. The lead compounds are reduced to yield lead metal. By changing the refining process antimony containing lead is also produced, which can be refined to soft lead. A typical recycling chart of LA batteries is shown in Fig. 8[54]. For damaged spent LA batteries, leaching with or without calcination of the disassembled materials is required while the morphology needs to be well controlled. In hydrometallurgical process lead oxide is produced which can be used directly in a new battery without any post processing. Compared to pyrometallurgical techniques the hydrometallurgical process has advantages such as low operating temperature, minimized dust and SO_2 emissions.

5 Novel Recycling Methods for Li-ion Batteries

Since LA batteries have achieved a high level of recyclability with the existing recycling methods, recent efforts have been focused upon Li-ion batteries to enhance its recyclability.

5.1 Direct Recycling of Li-Ion Batteries

The removal of cathode or anode material from the electrode for reconditioning and reuse in a remanufactured Li-ion battery is known as direct recycling. In principle, mixed metal-oxide cathode materials can be reincorporated into a new cathode electrode with minimal changes to the crystal morphology of the active material. The main recycling steps include mechanical separation of electrodes, washing, filtering, and drying. Direct recycling is vital towards recovery of critical metals in an economical and environment friendly process[84].

In direct recycling, the battery is first discharged, followed by completely dismantling the battery to the cell level, mainly by hand. Then the pouch cells are placed in an inert chamber to prevent fire or explosion and then opened and separated into anode and cathode. This step uses automation as a safety measure. The output from this step is the separated electrodes and separator foils, which are collected for plastic recycling. The recovered anode and cathode are washed with water at temperature of 20–30 °C and with air pressure of 90 bar to separate the aluminum foil

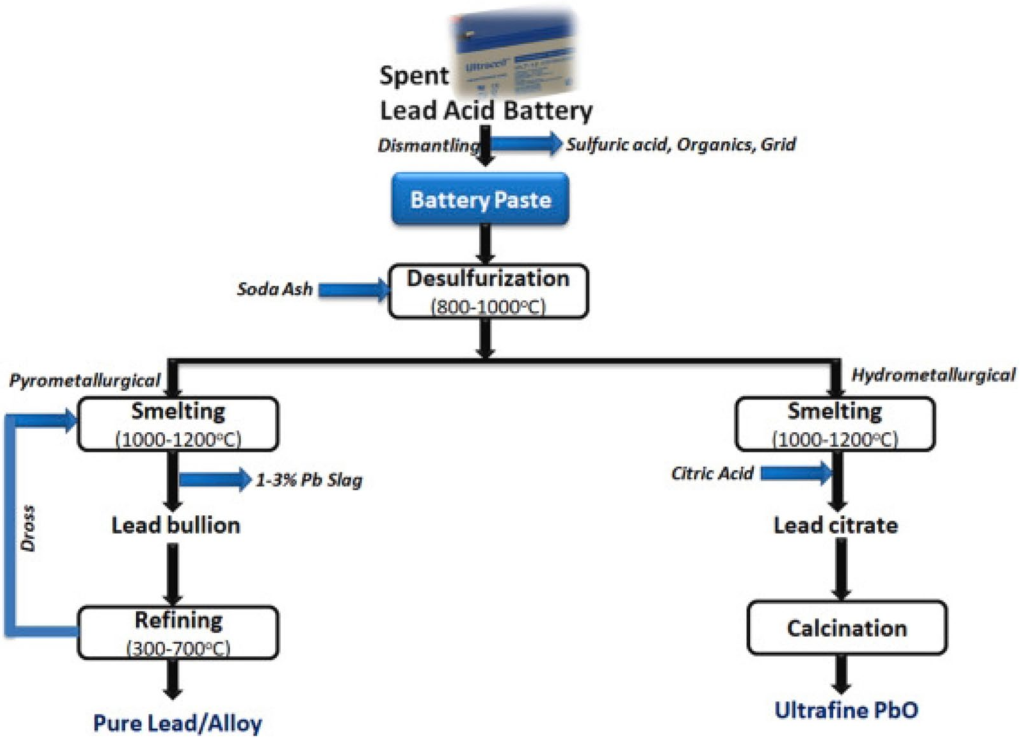


Figure 8: Typical flow sheet for processing of lead acid battery waste[54]. Reproduced with permission.

Table 3: Recoverable materials from spent Li-ion and LA batteries[76].

Pyrometallurgy	Hydrometallurgy	Direct
Copper compounds	Copper	Copper
Iron compounds	Steel	Steel
Co2+in output	Aluminum	Aluminum
Ni2+in output	Graphite	Graphite
Lithium compounds	Plastics	Plastics
	Lithium carbonate	LCO
	Co2+in output	NMC
	Ni2+in output	LFP
	Mn2+in output	

and the coating (active mass containing nickel, manganese, cobalt and carbon). The cathode active mass is filtered, pressed, washed and dried in a gas oven, and the recycled cathode materials thus obtained can be used for the production of new cells. The anode is treated similarly from which copper foil and graphite active mass are recovered. Copper foils are dried and sold and the recycled graphite material is not used for battery anodes but is used for other purposes. Table 3 shows a summary of recoverable materials from the recycling processes[76].

The drawback with the direct recycling method is that it is only applicable to pouch and prismatic cells and less suited for cylindrical cells. Additionally, direct recycling method falls short in accommodating different feedstocks that can result in contamination during processing, which ultimately decreases the quality of the recycled product.

5.2 Bioleaching and Biosorption Process

Bioleaching is a hydrometallurgical process, where biogenic hydrogen sulfide is used to aid the metal precipitation from mixed pregnant leach solutions. In this process microorganisms are utilized to digest the metal oxides from cathode selectively and reduce the oxides to produce nanoparticles[85–87]. Direct bioleaching, i.e., the employment of iron and sulfur oxidizing bacteria, is not found suitable for Li-ion batteries due to the polymetallic composition as well as the complicated nature of the spent Li-ion batteries. However, there is a lack of literature on using these two techniques specifically on Li-ion batteries and/or other e-waste[88].

Biosorption has recently been tested for successful recovery of Li among other metals present in Li-ion batteries. The success of any biosorption technique depends on the main adsorbent and

Table 4: Overall comparison of different recycling methods[90–92].

Recycle method	Advantages	Limitations
Pyrometallurgy	Simple processes, large-scale production capacity	High energy consumption, cost and harmful gases emission
Hydrometallurgy	High-purity materials recovered, low energy consumption	High reagent consumption, long processing time
Direct recycling	Low cost, energy consumption and pollution	Still in research phase, needs time to commercialize
Bioleaching	Environmentally friendly, low cost	Long time, easy contamination plausible

Table 5: Lithium recoverability from different companies from recycling processes [61].

Company	Li product	Recovery quality	Target use of recovery
Umicore[45,96]	Not recovered	–	–
Sumitomo-Sony[96]	Not recovered	–	–
Retriev Technology[96]	Li_2CO_3	No public data	Metal manufacture
Recupyl[61]	Li_2CO_3/Li_3PO_4	No public data	–
Akkuser[61]	Not recovered	–	–
Accurec[75]	Li_2CO_3	>99%[75]	Glass production/cathode synthesis[75]
Battery resources[97]	Li_2CO_3	High purity	Cathode powder synthesis[97]
Lithorec[98]	Li_2CO_3/LiOH	No public data	Cathode powder synthesis[98]
OnTo[99]	Li_2CO_3	99%[99]	Battery production

its affinity for Li[89]. When the affinity is greater for Li than other metal ions present in the pregnant leach solution, the recovery is expected to be high. Major limitations of the process include but are not limited to excessive processing time, poor recovery or separation yields, and lack of assessment of economic viability.

In Table 4, and Table 5 the summary of advantages and disadvantages of the different recycling methods is shown[90–92].

6 Challenges in Recycling Batteries

Since the batteries contain many toxic materials, it is important to make sure that the battery materials are recycled to protect people and the environment.

6.1 LA Batteries

The main battery materials in a typical LA battery are lead and antimony. Both materials are toxic in nature. These materials cannot be replaced without decreasing the efficiency or energy density of the battery but since they are in solid phase in the cell, the probability of leakage of these materials is low. However, another component which plays a key role in LA batteries is the electrolyte which is commonly made using sulfuric acid (H_2SO_4), which is also harmful. Since it is in liquid form, there is a higher probability of leak during transfer, production, and processing phases. This material is corrosive and if it comes in contact with humans it can cause irreparable harm[93]. Recycling of LA batteries consists of collecting the LA batteries, which is one of the primary ways for humans to get exposed to lead[94]. The success in achieving 99% recycling efficiency of LA batteries in EU and the USA[95] provides an inspiration for improving the recycling of other battery types.

6.2 Li-Ion Batteries

Extraction of Lithium is an environmentally adverse process. Production from brine involves drilling of salt flat (brine) then pumping the mineral rich raw solution to the surface. In this process the water tables are depleted, and aquatic life is adversely affected. Environmental impacts of Li mining have been reported in many Li producing countries that range from contamination of water and soil and impact on aquatic life. To decrease these adverse effects on the environment, recycled

Li is needed to reduce the consumption of the primary Lithium.

Recyclability of Li from Li-ion batteries is not efficient or plausible from the existing methods discussed in earlier sections. As can be seen in Table 4, some companies do not recover Lithium at all because of the high cost of recovering Li[61].

While at-source separation of batteries from other waste can help in reducing the overall recovery cost, the design of many electronic devices makes it difficult to separate them. In addition, many wearable devices have small size batteries which are difficult to handle. Overall, the challenges involved in Li- ion batteries recycling are: (1) the evolving chemistry of Li-ion batteries is making it difficult for the recycling technologies to keep pace, (2) the shipping and handling of Li-ion battery is expensive and difficult due to the potential explosion hazard, (3) initial manual disassembling process increases the recycling cost, (4) incomplete recovery of some valuable metals such as Li in pyrometallurgical recovery methods[53] and (5) lack of government regulations for standardization of designs, recovery and recycling of Li-ion batteries[100]. Some companies such as Li-Cycle (Canada) are making attempts to reduce the cost of Li-ion battery recycling and increase the Li and other valuable metals recovery; however, the details of this process have not been publicized yet.

7 Conclusions

The energy storage solution market is growing rapidly. While Li-ion batteries are considered the future, the market size of LA batteries is still growing due to the demand in automotive and grid scale storage applications. A comparison shows that the Li-ion batteries have higher energy density and longer cycle life but very low recyclability when compared with LA batteries. LA batteries have achieved a recycling rate of 99% whereas Li-ion has recycling rate of about 1%. This review article discussed the current technologies used for recycling Li-ion and LA batteries and the challenges faced by the respective industries. The rapidly evolving chemistry and cell design of Li-ion batteries are major challenges for the recycling industry to develop economical recycling processes. The success in achieving high recycling rate of LA batteries presents an example that a mature battery technology can incorporate near complete recycling in its life cycle. Use of many toxic materials in the current batteries makes it more desirable to develop efficient recovery methods.

Publisher's Note

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Declarations

Conflict of Interest

The authors identify no conflict of interest.

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