Lithium Batteries: Recycling Methods to Reduce their Environmental Impact

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***Abstract*—In recent years, the tech industry has seen significant growth, with lithium batteries (LIBs) playing a crucial role in powering portable devices. However, the widespread use of LIBs has raised concerns about their impact on the environment, from extracting raw materials to disposing of used batteries. The United Nations' Sustainable Development Goals stress the importance of sustainable waste management to tackle these issues. This paper focuses on the environmental impact of LIBs, covering their entire life cycle, from extract minerals to disposing of old batteries. It examines various recycling methods, including pyrometallurgical, hydrometallurgical, and direct recycling processes. This project proposes a method that integrates mechanochemical technology to improve LIB recycling efficiency. Mechanochemical processing offers benefits by reducing waste and enhancing material recovery, although there are still challenges related to the cost of reagents and efficiency. Adopting advanced recycling techniques, such as mechanochemical processing, can be possible a promising solution to address the increasing environmental concerns related to LIBs while also maximizing economic gains. This paper contributes to increasing awareness about LIB usage, disposal, and their environmental impact, highlighting the need for more sustainable recycling solutions.**

***Keywords:* lithium batteries recycling – pyrometallurgical recycling – hydrometallurgical recycling – cathode-to-cathode– mechanochemical recycling**

***Resumen*— En los años recientes, la industria tecnológica ha visto un crecimiento significativo, con las baterías de ion de litio (BILs) jugando un rol crucial en alimentar dispositivos portátiles. Sin embargo, el uso generalizado de las BILs ha incrementado preocupaciones acerca de su impacto en el medio ambiente, desde extraer la materia prima hasta el desecho de baterías usadas. Los Objetivos de Desarrollo Sustentable de las Naciones Unidas destacan la importancia de un manejo sustentable de los desechos para enfrentar estos problemas. Este artículo pone foco en el impacto ambiental de las BILs, abarcando el ciclo de vida entero, desde extraer los minerales hasta el desecho de baterías viejas. Se examinan varios métodos de reciclaje, incluyendo pirometalurgia, hidrometalurgia, y el proceso de reciclaje directo. Este proyecto propone un método que integra la tecnología mecano-química para mejorar la eficiencia del reciclaje de las BILs. El proceso mecano-químico ofrece beneficios al reducir los desechos y mejorar la recuperación de materiales, a pesar de que aún haya desafíos relacionados con el costo de los reactivos y la eficiencia. Adoptando técnicas de reciclaje avanzadas, como el proceso mecano-químico, es posible una solución prometedora para abordar la creciente preocupación ambiental relacionada hacia las BILs mientras también se maximizan las ganancias económicas. Este artículo contribuye a aumentar la conciencia acerca del uso de las BILs, desechos, y su impacto ambiental, resaltando la necesidad de por más soluciones de reciclaje sustentable.**

***Palabras claves:* reciclaje de baterías de litio – reciclaje pirometalúrgico – reciclaje hidrometalúrgico – reciclaje directo – reciclaje mecanoquímico**

I. INTRODUCTION

In the present century technological industry has grown enormously. In this context, batteries of lithium are more present than ever because nowadays they are a crucial component in portable devices, such as netbooks, notebooks, tablets, smartphones, among others. Since their invention in the 80s, lithium batteries (LIB) have been improved and their production has increased to satisfy the growing demand for their use in various devices.

LIB power other devices and, when those devices reach the end of their useful life due to battery depletion or other causes, the disposal of the device often leads to incorrect disposal of the battery. In this respect, sustainable waste management is discussed in the United Nations' Sustainable Development Goals (SDGs) Report, which sets goals for all the countries to comply with to take care of the planet. SDG #12 in particular aims to reduce the impact of technological waste on the environment to avoid damage to it and to humans [1].

Within this framework, numerous recycling processes can be implemented to transform the waste of LIB into raw material to manufacture new batteries or use their metals with other purposes. Each of these processes has very particular characteristics, with advantages and disadvantages in terms of efficiency, cost and complexity [2]. Recycling processes to manage LIB should then be analysed in order to reduce environmental impact.

To achieve this purpose, in this paper, in the second section, different methods of recycling are going to be reviewed and then, a method that result most convenient for companies or manufacturers in terms of practicality is going to be proposed. In the third section, this paper is going to propose a recycling route that makes it easy the disposal of batteries, their management and their reinsertion in the market. This paper is expected to contribute to raising awareness about the use and disposal of LIB and their impact on the environment.

II. ENVIRONMENTAL IMPACT OF LITHIUM BATTERIES

Nowadays, there is an increasing application of lithium batteries due to the advancement in energy storage technology. In consequence, the demand for consumer electronics and LIB powered devices such as laptops, smartphones, electric cars, etc. are increasing. This, along with the policies of first-world countries due to the interest in developing eco-friendly products, will significantly increase the demand for LIBs in the coming years [3]. Although the change is for a good cause, namely, reducing the environmental footprint, this situation has a background scenario related to the environmental impact of LIBs, from the extraction of raw materials to their manufacturing, until the end of life, which very likely involves their disposal in landfills [4].

To understand the environmental impact of LIBs, three subsections divide the important stages of the LIBs life cycle. The first one is about obtaining of minerals/metals to manufacture the batteries, the next one refers to the use of LIBs in devices, including accidents that could happen during their useful life, and the final subsection addresses the disposal or treatment of LIBs when they reach the end of their life cycle.

A. *Extraction of minerals*

The environmental impact of lithium batteries starts from their conception due the mining activity required for extracting raw material to produce them. To produce a LIB, several minerals/metals such as cobalt, copper, nickel, and lithium are necessary. These required materials are not present in large quantities in nature, so the exploitation of these resources, which is increasing due to demand, has a non-environmentally friendly intervention in nature, resulting in gas emissions due to mining activities in all the aforementioned sources, regardless of their size [4]. The economic factor also contributes to this situation, as mentioned before, due to the increasing demand for LIBs for electric vehicles (EVs) [4].

Regarding the synthesis of obtained metal ores, it is clear that the manufacturing process to obtain raw materials (metals) in industrial amounts consumes a lot of energy (electricity), which also contributes to the LIB life cycle footprint. However, the approach to LIB material extraction is not within the scope of this paper.

B. *Daily use of LIB*

LIBs undergo safety tests before their use. However, accidents can occur due to failures in the device that the LIB powers (or directly in the LIB), as well as their incorrect use. Following [5], incorrect use or mishandling refers to damaging the battery by cutting or drilling with sharp objects (knives, scissors, etc.) or causing deformities by hitting them. It almost always refers to a short circuit between battery terminals or an unexpected reaction from the chemicals inside the battery. Whatever the reason for the accident, the consequence is the same: a violent chemical reaction inside the battery that releases a lot of energy, igniting the compounds of the battery and resulting in an explosion and fires that can cause major damage to other objects, people, or even burn down a house in an extreme case. The aforementioned statement does not directly impact the environment, but it can cause significant harm to people, and in some cases, it can trigger major consequences such as fires in a landfill or grassland, escalating to a bigger environmental damage.

C. *End of life*

After the treatment and disposal at the end of its life cycle, a LIB can end up in two main destinations: a landfill or a treatment plant where it undergoes recycling processes to recover its compounds, particularly the valuable metals. As stated in [6], various processes, including hydrometallurgical or pyrometallurgical processes that involve heat or acids, are used to break down the battery into raw materials.

Both these processes and landfilling have significant environmental impacts, including gas emissions, toxic liquids, and the potential for chemical reactions leading to explosions in the case of landfilled batteries. However, there are other treatment processes like direct recycling or mechanical recycling that aim to be more environmentally friendly in recycling LIBs, using techniques such as manual disassembly.

As it been stated, LIBs have an impact on the environment during the process of extraction of materials, their use and their end of life. This paper focuses on the latter. The reason is because there is an important problem to solve in the LIB life cycle to make them a more sustainable cycle of production in order to avoid toxic waste and contaminating emission gases.

III. Recycling Methods

In the previous section, the problem of LIBs has been stated in detail. Therefore, the problem is going to be addressed by first reviewing recycling methods of the LIBs with their pros and cons. With this notion, a new recycling process is proposed with the aim of achieving an optimum balance between environmental impact and cost-effectiveness.

Recycling methods make use of different techniques to decompose the LIB and obtain raw material in different forms.

A. *Pyrometallurgical Process*

The pyrometallurgical process is commonly used in the industry. As described in [2], it involves exposing oxides like cobalt and nickel to high temperature to facilitate oxidation, during which the materials make the transition from oxides to metals resulting in a mixed metal alloy. The metals can then be separated and used to make new cathode material.

B. *Hydrometallurgical Process*

The hydrometallurgical process works by utilizing acids to dissolve the ions from the cathode, creating a solution which is a mixture if ionic species. These species can be recovered through precipitation or solvent extraction, and then they can react with other recovered materials to produce new cathode materials, as introduced in [2].

C. *Cathode-to-Cathode*

Not all battery components are equally important. Cobalt is the main objective of LIB recycling because of its high value. Recovery of cobalt from cathode by smelting (pyrometallurgy) or leaching (hydrometallurgy) recovers about 70% of the cathode value, and that offers an advantage for direct recycling, which is called cathode-to-cathode recycling.

In contrast with the previous process, cathode-to-cathode recycling, also called direct recycling, is less expensive. Direct recycling of the components of the LIB is done by physical processes, like gravity separation, which recover separated materials without causing chemical changes, enabling recovery of cathode material [2].

D. Processes Comparison

All the processes have a specific characteristic that differentiate them. Both direct recycling and hydrometallurgy start with dismantling or shredding the cells recovering the copper and aluminium foils as metals. In contrast, the pyrometallurgy feeds whole cells into a furnace and sends the copper to a mixed alloy product, the aluminium and lithium to the slag.

The three processes also have differences in terms of energy. Hydrometallurgy and direct recycling are processes which need low temperature and have a low consumption of energy but the pyrometallurgy is exactly the opposite, as it can be seen in Fig. 1. Following the characteristics in [2], the principal difference between hydrometallurgy and direct recycling is that direct recycling retains the cathode crystal morphology, while hydrometallurgy uses strong acid to dissolve the cathode and after leaching, then the dissolved constituents can be separated from each other and reused to manufacture new cathode material.

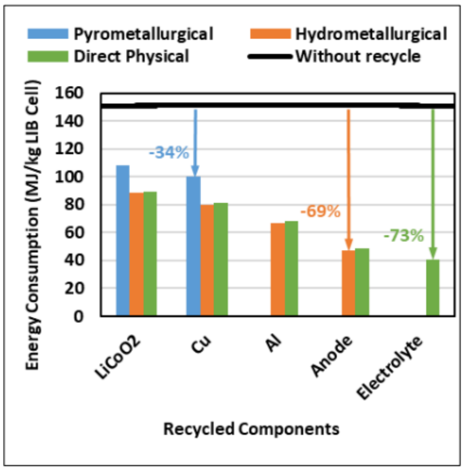

Fig. 1. Comparison between processes in terms of energy consumption [2]

E. A New Step for Hydrometallurgy

The different processes analyzed have their advantages and disadvantages in terms of materials recovered, energy consumption and environmental impact. Also, they seem to be very different and unmixable processes. However, there are two processes that complement each other, namely, the hydrometallurgical process and direct recycling. Both processes have low energy consumption (in comparison with the pyrometallurgical one) and the hydrometallurgical process has a first step of shredding and crushing the LIB (like direct recycling). This leads to the possibility of creating a different process or an improvement of a process that involves the best of the two previous methods mentioned before. It is important to achieve a lower environmental impact choose properly the different steps to recover the compounds of a LIB with lower energy consumption and fewer gas emissions.

Considering the lower gas emissions of direct recycling, it is preferable to carry out a process that tends towards direct recycling due to the few steps that it requires. The proposed method consists in applying direct recycling steps in the cases that hydrometallurgy cannot recover certain materials or it results in a considerable amount of gas emissions. Also, it is essential to apply direct recycling to reduce waste that is going to be landfilled.

Research about recycling processes and the way they can be combined to increase the efficiency shows that there is a more efficient way to recycling batteries more efficiently. It is the adoption of mechanochemical technology. This technology is a solution that benefits many aspects of the battery recycling process and it is linkable with the hydrometallurgy process.

The mechanochemical technology consists of a rotative drum with milling balls that are driven by the drum and the mechanical energy (or kinetic energy) that they obtain is transferred to the batteries by impacting or hitting them [7]. This process reduces the batteries to very little crystal pieces with a very little particle dimension. The Its major benefit is that it facilitates a post leaching treatment with solvents and other acids or chemical reagents, to continue with a hydrometallurgical process [7]. The reason why it is easier for a post leaching treatment is because the size of the LIB compound particles will then require less solvent and other reagents and acids to make new compounds that are useful to separate desirable metals or material [7].

There are many benefits of the mechanochemical process. This process is more efficient because by provoking chemical reactions the LIB is reduced to little crystals [7]. After that, the compounds obtained can be leached again and separated or directly separated if they are the intended compound.

IV. ADVANTAGES AND DISADVANTAGES OF MECHANOCHEMICAL PROCESS

The mechanochemical process is an efficient change in the LIB recycling process. It is versatile and can be adapted according to the recycling facilities interested in certain materials or metals. This process can optimize other processes if they are combined (for example, applying the mechanochemical process and the hydrometallurgical process afterwards). This means that lower energy consumption and less waste is generated. However, there are some inconveniences and aspects to be improved, such as the lower performance. Although this process consumes less energy, its efficiency is about 25% [7]. Also, if reagents are added in the mechanochemical process to obtain compounds in an easier way, such compounds are usually expensive or they require more time to react if they are inert gases. It reduces the economic benefits of mechanochemical application.

V. CONCLUSION

The LIBs are expanding their market every day without stopping. For this reason, it is very important to implement systems with the characteristics explained in the entire paper. Nowadays, the processes for recycling LIBs are not developed with advanced technologies, and obviously, they can be improved in the years to come. However, the emergence of new methods, such as the mechanochemical processes, opens doors to investigate new strategies with the aim of avoiding the contamination of the environment by LIBs and achieving economic benefits.

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