ASPECTS RELATED TO CURRENT RECYCLING METHODS AND TRENDS IN IMPLEMENTING THE PRINCIPLES OF THE CIRCULAR ECONOMY FOR LITHIUM-ION BATTERIES

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Abstract: Renewable energy, electric vehicles, personal electronics and hand tools all have in common: lithium-ion batteries. In the context of the circular economy, there is the issue of recycling and reusing batteries. Li-ion batteries can be recycled, but this process is expensive and, for now, the material recovery rate does not exceed 20%. However, research is progressing rapidly, and in the laboratory, scientists have managed to reach 80% recovery levels.
In case of reuse, a Li-ion battery can reach approximately 10,000 charging and discharging cycles, which can mean a lifespan of several months in some devices or more than 15 years in the case of storage applications. energy.
Therefore, used batteries can be tested for capacity assessment and reused in less demanding applications.
Transitioning to a circular economy is not only vital to the preservation and protection of our planet's natural resources, but also to the success of businesses.
In Europe, electric vehicle manufacturers have successfully reused batteries used in various types of energy storage systems, from their use in small residential devices to supporting industrial solutions.

Keywords: EV battery recycling, Lithium-Ion Batteries, Circular Economy.

1. Introduction

Rechargeable batteries have become indispensable in everyday life, being present from mobile phones to laptops, from e-bikes to electric cars. Lithium-ion batteries of various types are the most common energy storage technology for both Electric Vehicles (EV) and Energy Storage Systems applications, but these batteries include many pollutants that are classified as hazardous waste at the end of their life. Given the gigabyte-hour (GWh) deployments of planned energy storage systems, the industry needs to have a vision for managing the fleet of advanced industrial batteries that are being implemented now and will need to be managed responsibly in the years to come [1].

Electric vehicles play a key role in the transition to a low-carbon transmission system, but used batteries must be recycled and hazardous materials must be collected safely or neutralized.

The European Commission proposes modernization of EU battery legislation, presenting the first of the initiatives announced in the new Circular Economy Action Plan [2]. Batteries placed on the EU market must become durable, high-performance and safe throughout their life cycle, being essential for the objectives of the European Green Pact and helping to achieve the zero pollution reduction target set out in this pact. They promote competitive sustainability and are needed for green transport, clean energy and climate neutrality by 2050.

2. Enablers and Perspectives on the Evolution of Electric Vehicle Batteries

In its 2020 Strategy for Sustainable and Smart Mobility [3], the European Commission has set an intermediate target of at least 30 million zero-emission vehicles by 2030, as well as the 2050 target for zero-emission vehicles to be most of the fleet, which is a significant increase from the approximately 2 million electric vehicles currently registered in the EU.

Battery Regulation – COM proposal 10 Dec 2020 [4] is the proposal to ensure that only high quality batteries are placed on the EU market and that those batteries are produced with a low impact on the environment, using materials that have been obtained in full compliance with social and environmental standards. Batteries should also be long-lasting and safe and should be collected and recycled at the end of their life. Intended to replace the Batteries Directive (2006/66/EC), the new battery regulation imposes new requirements on the sustainability and safety of batteries for electric vehicles and rechargeable industrial batteries, including the carbon footprint, the content of recycled raw materials (cobalt, lead, lithium and nickel), electrochemical performance and durability, QR code, battery passport, etc.

The companies' concern for the environment and the new pollution rules have made it possible to reinvent electric cars and obtain advantages, the highest of which is zero emissions when using an electric vehicle. Other advantages are the lower price of electricity compared to diesel or gasoline, the bonuses that states are willing to give to those who buy such a vehicle, reduced noise pollution.

Because electric machines use fewer moving components, periodic overhauls generate lower maintenance costs throughout their life.

However, the high purchase price is a disadvantage of electric cars, even with government bonuses such a model costing more than a car equivalent to a diesel or gasoline engine.

However, the battery is widely considered to be a limiting factor for electric vehicles, the lack of autonomy being cited as one of the main reasons that prevent the transition from petrol or diesel vehicles to electric ones. As the range of electric vehicles is generally lower - around 380 km, an average calculated for 10 electric cars currently on the market - than that of traditional vehicles, electric vehicles need to be charged more frequently [5].

Another major drawback is the fact that the number of public outlets is not high, even if in recent years, the charging infrastructure has developed a lot and the European Union proposes a series of projects to support the installation of stations for recharging electric cars.

But in the current climate emergency, zero-emission vehicles have become a priority for governments and manufacturers around the world as technologies have improved considerably over the past decade, with some electric car batteries now reaching a range of up to 400 miles (about 640 km) [6].

In 2017, approximately one million electric vehicles (EVs) were produced; by the end of this decade, another 30 million will likely be on the way, turning the EV industry into the largest consumer of lithium and cobalt.

Electric vehicles will be the driving force behind the demand for lithium-ion batteries [7]. Figure 1 shows the evolution of the demand for electric batteries for the period 2015–2020 and the estimated demand until 2035.

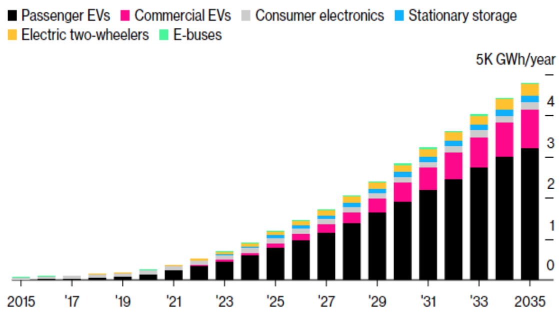

Figure 1: Annual GWh demand 2015 -2035
[Source: BloombergNEF Long-Term Electric Vehicle Outlook, June 2021]

To meet the growing demand for these portable power plants, Tesla opened its first gigafactory in 2016 in the Nevada Desert and launched a global race to change the world to electric vehicles and energy storage. Gigafactory Berlin - Brandenburg is the first location in Europe to produce Tesla vehicles and the most advanced, sustainable and efficient unit to date. To be completed in 2021, the factory will produce hundreds of thousands of Model Y vehicles and millions of batteries [8]. These multi-gigawatt-hour facilities are an order of magnitude larger than their predecessors, and the impact on the supply chains that power them has been profound. Understanding the plans of all current and emerging players in the field of LIBs is crucial to assessing the fate of electric vehicles and reducing the world's dependence on fossil fuels through energy storage. Today's lithium-ion battery is what was the barrel of oil in the twentieth century - the force that holds these energy megatrends together [9].

Even if it is hampered by the current pandemic, the renewable energy industry is already entering a new phase of growth in terms of growing demand, cost competitiveness, innovation and collaboration between nations. The proliferation of electric vehicles and other energy storage systems is expected to cause a sharp increase in demand for lithium and other elements used in Li-ion batteries [10] which creates two problems: first, much of the critical material it is imported from countries with questionable work practices and poor environmental regulations; second, batteries contain toxic and flammable chemicals that require proper handling throughout the battery life cycle [11].

The good thing is that each of the above problems is actually the solution to the other: although there is not enough lithium, cobalt and nickel to satisfy the EV industry, Li-ion batteries at the end of their life cycle can be successfully exploited to recover these elements because the extraction of substances by recycling has a much smaller environmental footprint than the extraction of raw materials from the soil.

However, the recycling of Li-ion batteries is not done on a large scale, due to a combination of economic and technological factors. Currently, less than 5 percent of all end-of-life Li-ion batteries are recycled, but that is about to change, thanks to innovative researchers and companies [12].

3. Current Technology of Electric Car Batteries

How a battery and the car's electric motor work together is surprisingly simple - the battery connects to one or more electric motors that drive the wheels. When the accelerator is depressed, the car instantly supplies power to the engine, which gradually consumes the energy stored in the batteries. Electric motors also work as generators, so when they no longer accelerate the car slows down turning the movement into electricity - this happens more strongly if the brake is applied. This regenerative braking recovers energy that would otherwise be lost, storing it back in the battery and thus improving the autonomy of the car.

EVBs undergo "discharge" cycles that occur while driving and "charging" when the car is connected. Repeating this process over time affects the amount of charge the battery can hold. This decreases the interval and time required between each trip for loading. Most manufacturers have a five to eight year battery warranty. However, the current forecast is that an electric car battery will last between 10 and 20 years before it needs to be replaced [13].

A lithium-ion battery (LIB) is a type of rechargeable battery used in electric vehicles as well as in a range of portable electronics. LIBs have a higher energy density than typical lead-acid or nickel-cadmium rechargeable batteries. Lithium is also the lightest of all metals. This means that battery manufacturers can save space by reducing the overall size of the battery pack. Lithium-ion batteries are also safer than many alternatives [14], but battery manufacturers need to ensure that safety measures are in place to protect consumers in the unlikely event of a battery failure.

However, the stable operation of the LIB under normal conditions significantly limits the damage to the battery in the event of an accident. As a result of all these measures, current LIBs are much safer than previous generations, although further developments are still needed to further improve battery safety [15].

When comparing performance, several characteristics must be considered, including cost, materials, lifespan, load capacity, safety, power and energy. A key element for the autonomy of electric cars is the amount of energy that the battery can store: this is known as its specific energy density.

4. Circular Economy - the Second Chance at Life of Batteries

4.1. Reuse of Electric Vehicle Batteries

The Circular Energy Storage report [16] shows that the average age of light duty EV batteries will be 14.7 years when they reach the first end of life, with 50% having reached end of life after 15 years. Also, the battery age is not only connected to battery performance but as much to the actual application, ownership, value and user behavior.

After the old battery is removed from the vehicle, it is evaluated and usually enters a second life. Despite having a smaller storage capacity, the battery can still serve a useful purpose. Old batteries can be used in applications that are not as demanding as powering a vehicle. For example, a battery can be used for stationary energy storage to support the local utility company's electricity grid. Redirecting the battery to a second circuit of use, where the useful life is extended, offers alternative energy storage services, thus reducing the environmental impact per kWh provided by the battery. A representation of battery life from a circular economy perspective is shown in Figure 2 [17].

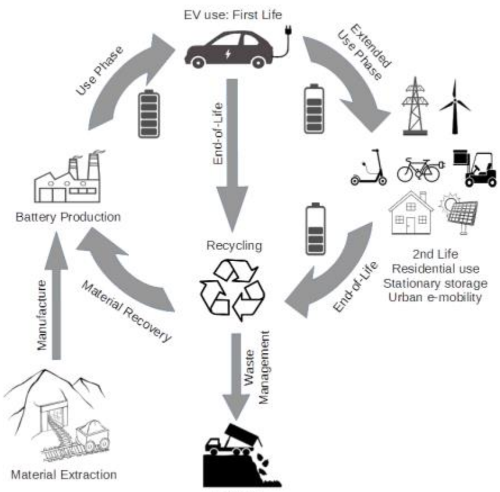

Figure 2: Battery life cycle in a circular economy perspective
[Source: Kotak, Y et all, End of Electric Vehicle Batteries: Reuse vs. Recycle]

The transition from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries, by obtaining more results from used batteries and by capitalizing on the end of life.

4.2 Recycling Li-ion Batteries

Lithium-ion batteries have been recycled for more than 15 years, but with different efficiencies and recovery rates. Recycling must be managed properly, as toxic chemicals inside old batteries can lead to water and soil contamination. As part of the recycling process, they are melted to recover lithium, cobalt and nickel. However, this can be costly, so reusing used batteries can be more cost effective. Many EVBs still have up to 70% of their capacity [18], which means they can be used for many other energy storage needs.

Lithium-ion batteries, which use hazardous metals, stain the green image of electric vehicles. Recycling to recover those precious metals would minimize the social and environmental impact of mining, save millions of tonnes of batteries from landfills and reduce energy consumption and emissions from battery manufacturing.

But as the EV battery recycling industry begins to grow, convincing carmakers to use recycled materials remains a difficult task, as people's impression is that recycled material is not as good as virgin material and battery companies still hesitant to use recycled material in their batteries [19].

5. Lithium Ion Battery Recycling Methods

Recycling for LIB usually involves both physical and chemical processes [20]. Due to the complex process of assembling the LIBs and the wide variety of electrodes, the process of battery recovery involves a high risk of accidents due to explosion, combustion and the resulting harmful gases [21]. To reduce this risk, used LIBs should usually be discharged before recycling.

Physical processes usually include pretreatment and direct recovery of electrode materials [22]. These processes usually include disassembly, crushing, screening, magnetic separation, washing, heat treatment, etc.

Chemical processes can be divided into pyrometallurgical and hydrometallurgical processes, which usually involve leaching, separation, extraction and chemical/ electrochemical precipitation.

Currently, the hydrometallurgical process shown in Figure 3 is commonly used to recover LIBs after pretreatment.

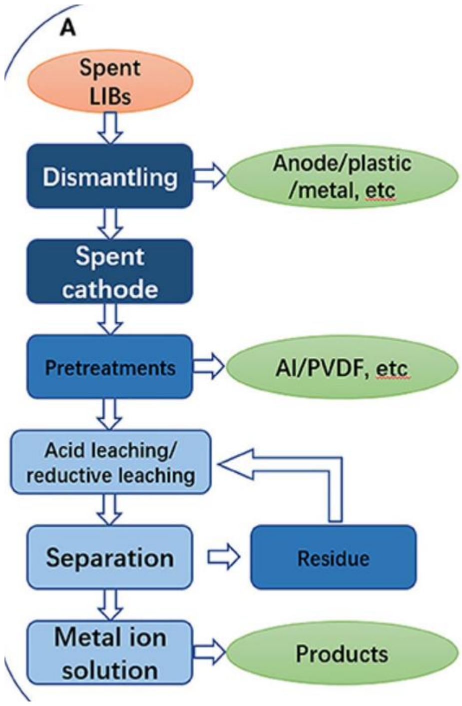

Figure 3: (A) Hydrometallurgical process
[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries"]

The pyrometallurgical process (Figure 4) is widely used for the commercial recovery of Co.

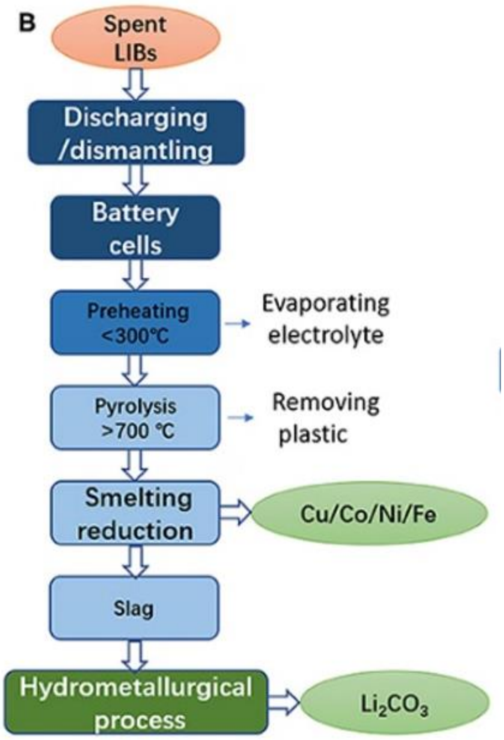

Figure 4: (B) Pyrometallurgical process
[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries]

The direct physical recycling process (Figure 5) is a process of recovering useful components from used LIBs without using chemical methods.

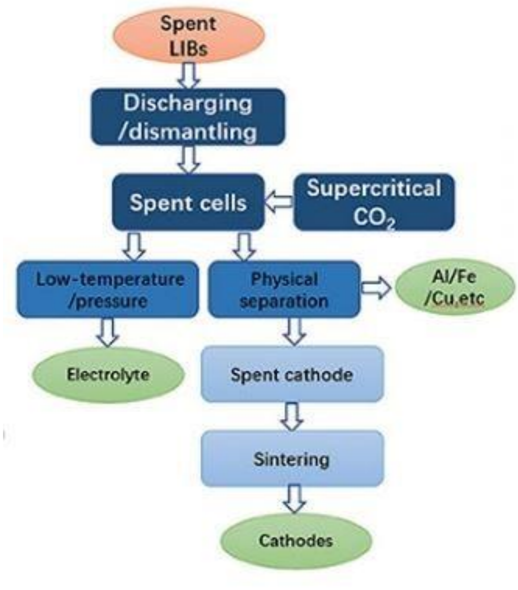

Figure 5: (C) Direct physical recycling process
[source: Zhou Li-Feng, et all „The Current Process for the Recycling of Spent Lithium Ion Batteries"]

A hydrometallurgical process - which uses an acidic solution to separate complex chemicals into individual elements - is more expensive, consumes more energy and is more complex, but has the advantage of being interoperable between different systems in terms of cathode chemistry [23]. However, it recovers only about half of the battery mass. Figure 6 shows the direct recycling and recycling by hydrometallurgical process.

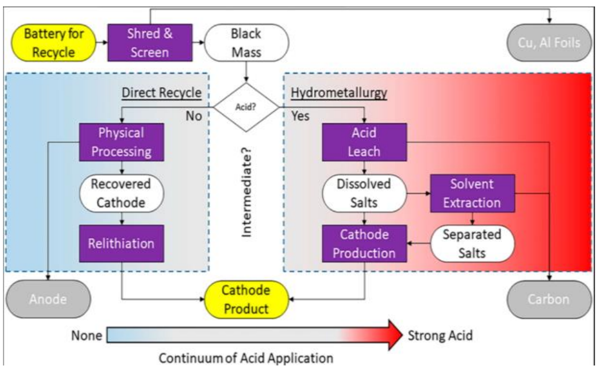

Figure 6: Direct recycling vs. hydrometallurgy
[source:https://www.engineering.com/story/closing-the-loop-on-li-ion-battery-recycling]

The U.S. Department of Energy established the ReCell Center in early 2019 to develop robust LIB recycling technology that would be economical even for batteries that contain no cobalt. The central feature of the technology is recovery of the cathode material with its unique crystalline cathode morphology intact in order to retain its value and functionality [24].

This allows a reduction in the GHG intensity of the value chain by 34 megatons (Mt), while creating an additional economic value of about $ 35 billion. Grid Vehicle (V2G) solutions could reduce costs for electric vehicle charging infrastructure by up to 90%, and in 2030 could cover 65% of demand for global battery storage networks [25].

The concept of direct recycling, patented in the United States for the first time in 2009 [26], is simple: the crystalline structure of the cathode must be kept intact. ReCell R&D defines direct recycling as the recovery, regeneration and reuse of battery components directly, without destroying the chemical structure. It has also been called direct cathode recycling and cathode-to-cathode recycling.

By recovering the cathodic material, several energy-consuming and expensive processing steps can be avoided; this is shown schematically in Figure 7. The scope of ReCell R&D also includes the recovery of as many materials as possible, in accordance with the principles of the circular economy. Not only does the recovery of multiple materials offer potential additional revenue, but the costs and other impacts of waste treatment can be avoided.

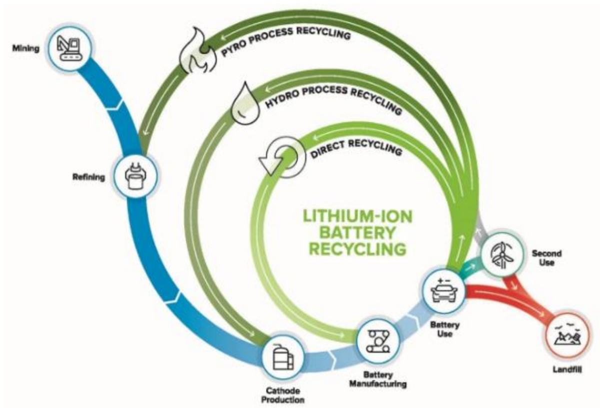

Figure 7: Lithium-ion battery lifecycle
[source: Gaines, L.; Dai, Q.; Vaughey, J.T.; Gillard, S. "Direct Recycling R&D at the ReCell Center". Recycling 2021]

When we say that an EVB has reached the end of its useful life, this does not mean that the battery is discharged - only that its storage potential has been reduced to about 80% of its initial capacity. The battery is still able to power the vehicle, but with less autonomy. These batteries do not need to be recycled at this time; instead, they can be reconditioned and reused in stationary applications, such as home energy storage systems, where the energy-to-weight ratio is not a factor. This addresses the issue of short-term landfill, but these batteries will eventually lose all energy storage capacity, so for the purpose of this discussion, we will assume that they are beyond the second stage of use and have no other value than a source of materials.

Li-Cycle Method: Spoke & Hub technologies from Li-Cycle [27] use a combination of safe mechanical size reduction and recovery of hydrometallurgical resources designed specifically for recycling lithium-ion batteries.

Li-Cycle stated that its method can recover 95% of a battery's materials using an environmentally friendly, safe, scalable and economically viable process.

Li-Cycle handles hazardous materials in strategically placed spaces with modular, scalable facilities that unload, disassemble, crush and sort - before transporting safe components to a central chemical separation hopper. The process recovers graphite, cobalt, nickel, copper, manganese and lithium from current Li-ion batteries.

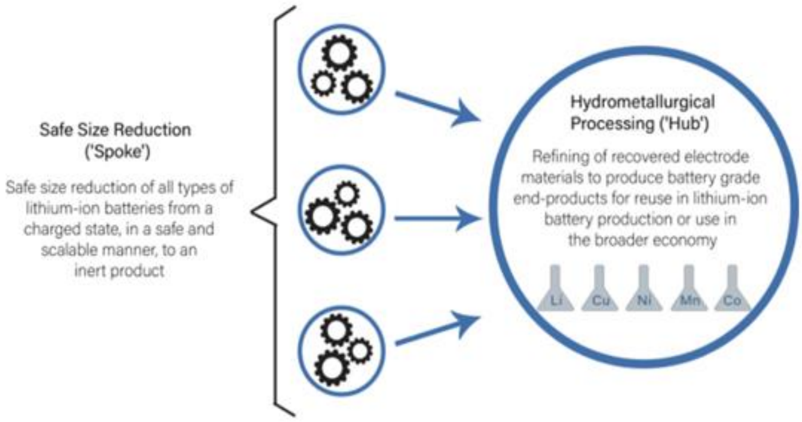

Figure 8: „Spoke and Hub" Method from Li-Cycle
[source: https://li-cycle.com/technology/]

Li-Cycle started in 2016, conducting two years of research and development before building a demonstration hub.

Material recovery with the Duesenfeld recycling method: Duesenfeld [28] claims that his recycling process can recover over 90% of a battery's material, using an environmentally friendly method that avoids the energy-intensive smelting process used in most battery recycling operations. For safety, Duesenfeld uses a decentralized system that minimizes travel distance to its recycling facilities. Upon arrival at a collection unit, the batteries are discharged and disassembled slowly. The cells are then crushed in an inert nitrogen atmosphere to prevent spontaneous ignition. The electrolytes are evaporated and recovered in vacuo, while the crushed material, which is now safe to transport, is sent to a central plant for further processing. After mechanical sorting, the company's patented hydrometallurgical method separates the remaining material to recover cobalt, lithium, nickel, manganese and graphite.

6. Automakers are Exploring Ways to Profit from used Batteries

Most of the time, the batteries of electric cars receive a second chance at life after they no longer serve the purpose for which they were built - they are used in charging stations on highways or become energy generators for homes.

In Japan, Nissan has repurposed batteries to power streetlights. It also leverages used Leaf batteries in autonomous robots that deliver parts to its car factories [29].

In Michigan, GM is using repurposed batteries from Chevy Volts to back up its data center.

In Europe, Volkswagen has already opened a recycling station in Salzgitter, Germany where batteries will be recycled after they can no longer be reused [30]. The capacity is 3,600 battery packs per year in the first phase, pilot.

The batteries - at the end of life - will be completely discharged, dismantled, and the components will be ground individually and dried. Through this process, the car company hopes to recover the raw materials needed to produce new batteries, such as copper, aluminum, lithium, manganese, cobalt and graphite.

Volkswagen anticipates that it will not receive a large number of batteries in the recycling plant from its electric cars until the end of the decade, so the Salzgitter project will start as a pilot, with the possibility of increasing capacity.

In Paris, Renault has batteries backing up elevators. Renault, the market leader in electric cars in Europe, recycles all used batteries from the models it sells. The company does this in partnership with Veolia and Solvay. The consortium wants to recycle batteries from any car manufacturer in the future and reach a market share of 25% in the field. Companies do not do this only out of civic responsibility.

The material resources used in batteries are limited, and their recovery is essential in the medium and long term.

7. European Initiatives to Promote Electric Battery Recycling

Electric cars use a lot of batteries to store energy, and in a few years they will have to be recycled. There are no factories in this segment in the European Union yet, but Poland is preparing to build the first factory in the European Union to recycle batteries for electric cars [31]. Elemental Holding Group announced it has received a 25m-euro loan from the European Bank for Reconstruction and Development (EBRD) to build the first plant in the European Union to recycle Li-Ion car batteries and other metal-containing waste . The Polish state will also be involved in this project through the Polish National Center for Research and Development, as well as the European Commission. The project is a large one, with the Polish group intending to reuse recycled materials to produce new batteries.

The first battery recycling plant for electric vehicles in the Iberian Peninsula will be built in Cubillos del Sil (Castilla y León region) and will come into operation at the end of 2023 [32]. The new battery recycling plant is one of seven projects recently approved by the Spanish Ministry of Ecological Transition, the regional government of Castilla y León, the municipalities of Ponferrada and Cubillos del Sil, the University of León and Endesa.

European Commission approves € 2.9 billion in state aid for a new continental alliance to support battery production for electric cars and the transition of carmakers [33]. The alliance consists of 42 companies from 12 European countries, including BMW, the German subsidiary Tesla, Enel X, InoBat and Varta and will carry out the project called "European Battery Innovation", designed to support value chains in battery production.

The project will be funded by Germany, France, Austria, Belgium, Croatia, Finland, Greece, Sweden, Spain, Poland, Sweden and Slovakia.

The European Commission also wants to attract 9 billion euros from private investors. The 12 EU Member States will fund research and innovation in the battery sector, covering the entire process of obtaining them, from raw material extraction, design and production, to their return and recycling in a circular economy, with a strong focus on durability. The EC is expected to contribute to the development of a whole new set of technological breakthroughs, including various cell chemistry and new production processes, as well as other innovations in the battery value chain, in addition to what will be achieved with the first IPCEI battery (Important Project of Common European Interest).

8. Conclusions

In the context of the circular economy, there is also the issue of recycling and reuse of rechargeable batteries. Li-ion batteries can be recycled, but this process is expensive and, for now, the material recovery rate does not exceed 20%. However, research is progressing rapidly, and in the laboratory, scientists have managed to reach 80% recovery levels.

In case of reuse, a Li-ion battery can reach approximately 10,000 charging and discharging cycles, which can mean a lifespan of several months in some devices or more than 15 years in the case of storage applications. energy.

Therefore, used batteries can be tested for capacity assessment and reused in less demanding applications.

In Europe, electric vehicle manufacturers have successfully reused batteries used in various types of energy storage systems, from their use in small residential devices to supporting industrial solutions.

The convergence of digital technologies and the urgent need for a low-carbon economy have disrupted traditional value chains and created avenues for the emergence of innovative solutions and opportunities in electric transport. These trends fuel innovation - where lower weight, greater autonomy, comfort, safety and a lower carbon footprint are the desired solution.

The number of electric cars sold in the European Union is growing dramatically from year to year, and by 2030 Member States want them to become the majority to the detriment of fossil fuels. The road is long, but the European Union's policy for the accelerated development of this sector will certainly bring results.

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