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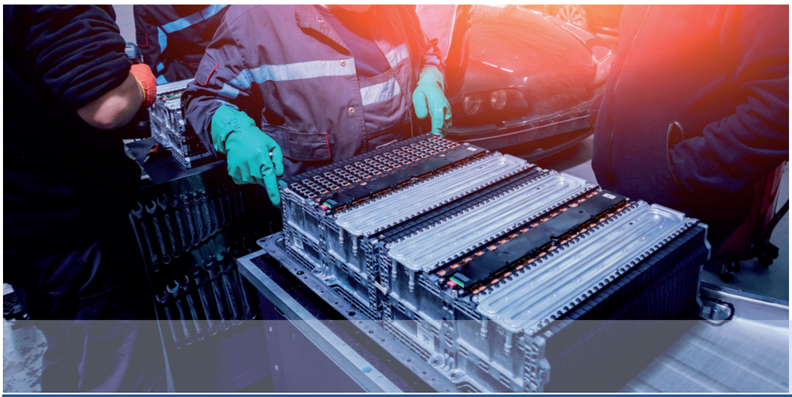

THE RECYCLING OF LITHIUM-ION BATTERIES

A Strategic Pillar for the European Battery Alliance

Raphaël DANINO-PERRAUD

March 2020

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Executive Summary

Although it is still marginal, the market for electric vehicles (EVs) is growing. According to the French Institute of Petroleum and Renewable Energies (IFPEN, Institut Français du Pétrole et des Énergies Renouvelables), EVs accounted for a little more than 2% of the light vehicle market in 2019. This was up by 54% compared to 2018, but EVs still only represent 0.8% of the global car fleet. That said, the International Energy Agency (IEA) estimates EVs could make up between 15% and 30% of vehicle sales in 2030. However, while European manufacturers have so far developed EVs such as the Renault Zoé or the BMW i3, they are highly dependent on Asian companies for the supply and manufacture of materials for cells and electric batteries, such as nickel, cobalt, lithium used to build precursors, or cathodes and their components. Asia provides more than 90% of world car battery output, half of which comes from China alone. European dependence is not only related to the manufacture of batteries, but occurs throughout much of their value chain, from extraction and processing of raw materials to the preparation of necessary treatment processes for recycling. The recycling market for batteries from small electronic objects (smartphones, computers, tablets, etc.) has also been led by Asian countries.

These imbalances have been identified by the European Commission (EC), which launched the European Battery Alliance (EBA) in 2017. Its aim is to make up for part of the backlog accumulated in the various segments of the battery value chain, and especially in recycling activities. The European Union (EU) carbon neutrality objective and the implementation of the Green Deal will accelerate the decarbonisation of the transport sector through the roll out of the electric mobility. This strengthens the strategic importance of the EBA and notably of developing a robust recycling industry, both from a geo-economic and environmental standpoint.

The recycling potential of batteries in the EU is significant and represents a triple challenge: i) environmental, because recycling allows energy savings compared to mining; ii) economic, because the development of a recycling infrastructure and an industrial ecosystem linked to electricity storage will create jobs and value; and iii) strategic, because it will allow the recovery of mineral resources which the EU does not exploit on its own lands, and which can be re-injected directly into EU industries.

However, there are many obstacles as the market is still uncertain and not very mature. The number of EVs is marginal, and most have not yet reached the end of their lives. This leaves many questions open about batteries' life spans, their collection, their condition and their adaptability to recycling processes. The lack of knowledge about the manufacture and composition of batteries is an obstacle to the efficiency of recycling processes, and can even lead to technical accidents. Despite significant growth, the battery market remains characterized by rapid technological developments, which have a direct influence on the raw materials used. There are also many types of batteries used at a given time, which makes standardization of industrial recycling processes difficult and challenges their economic viability. Raw material markets are in turn subject to a degree of financial volatility which makes investments in recycling uncertain. Thus cobalt, considered to be the most profitable metal to recycle, saw its price triple between 2017 and 2019, then being divided by four in a few months, before rising again, though without returning to its previous levels. In addition, the growing use of nickel, which will partially replace cobalt by 2021, is forcing companies to change their operations from cobalt to nickel. There are similar questions about the "second life" for these batteries which could then be employed for stationary uses. These questions remain pending, and will only find their answers through the actual "practice" of recycling by European industry. The latter for its part still suffers from a lack of international players (with the exception of Umicore) and from the fragmentation, or even an absence, of certain segments of the value chain.

It is therefore necessary to provide the European industry with the regulatory and financial means to implement such "practice". Thus, depending on the different stages of the battery life cycle, regulation should impose precise standards to encourage the sustainability of the European battery industry's productive model as well as its integration. For this, mining should be favored which is environmentally and ethically responsible, as should be the production of secondary raw materials through recycling. The processing of the latter should be facilitated by eco-design and eco-manufacturing standards for batteries, permitting the standardization of manufacturing and hence the recovery of materials at lower costs. This will involve: rethinking the targeting and accounting of recycling; reorganizing collection systems by industries in avoiding distortions to economic models; implementing the certification of collection and recycling channels; and more importantly, speeding up the revision of the EU Batteries Directive in order to adapt it as quickly as possible to the new challenges faced by the industry. At present, the recycling obligation for lithium-ion batteries is only 50%, whereas it is 90% for lead-acid batteries. A life cycle analysis (LCA) approach also needs to be adopted, in order to measure the carbon impact of batteries during manufacture, their use or even their end-of-life management. This would allow better control of imports with excessive carbon footprints, or of exports of end-of-life batteries to countries that do not meet minimum environmental standards.

More generally, a systemic vision is necessary to design a framework for an integrated European industrial ecosystem, which allows horizontal cooperation between companies, while being supported financially, legislatively and strategically by Member States and the EC.

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Introduction

The lithium-ion battery (LIB) results from progress made since the invention of the lead battery in 1859 throughout the 19th and 20th centuries. In 1986, the Japanese company Sony began to develop the LIB which was first commercialized in 1991 (Le Cras et Bloch, 2016). At that time, these batteries were only used for some niche markets or small electronic devices, but several factors contributed to enlarging their scope of application. First of all, the digitization of our societies has led to a more intensive use of LIB in small electronic devices such as (smart)phones, computers and notebooks: in 2018, 1.55 billion smartphones were sold, and it is estimated that 5 billion will be put on the market in 2020 (*Berthoud et al*, 2018).

The low-carbon energy transition will also increase the need for LIBs, as they are also used in EVs and hybrid vehicles (PHEV) in order to reduce carbon dioxide emissions as well as for stationary storage, to compensate for the intermittency of renewable energy sources and so maintain grid stability. In 2018, two million of EVs were sold, and the global stock reached 5.1 million vehicles, with an estimated 2.1 million additional sales in 2019[1]. Sales are expected to reach 4 million in 2020. While China is the main market, the EU represented 1.2 million of the global vehicle stock in 2018, and 385,000 in sales. According to an IEA scenario, the sale of EVs should increase to 23-40 million in 2030, for a stock of 130-250 million (IEA, 2019).

In 2000, LIBs only represented 1% of the stationary storage market, but this had increased to 21% in 2016 and should continue to grow, according to the consultancy firm Avicennes Energy (Pillot, 2017). In turn, energy storage capacity (not including pumped hydropower) around the world should develop fast, rising from 9GW/17GWh in 2018 to 1,095GW/2,850GWh by 2040, to better manage output from intermittent technologies (wind turbines, solar panels, etc.; Bloomberg, 2019).

There are several types of batteries. In 2016, the lead-acid batteries used in thermal engines represented 90% of the market, whereas NiMH batteries (nickel metal hybrid) used in PHEV and some portable

1. M. Holland, "Fossil Vehicle Sales In Global Freefall — Down 4.7% In 2019! Electric Vehicle Sales Continue to Grow", CleanTechnica Report, January 18th, 2020, available at: https://cleantechnica.com.

applications and NiCd batteries for industrial niches (nickel-cadmium) had a respective shares of 1% and 0.5%. LIBs have a market share of 8%, but several chemical varieties are available (NMC for nickel-cobalt-manganese; LCO for lithium-cobalt oxides; NCA for nickel-cobalt-aluminum; LFP for lithium-iron-phosphate, etc.). Others like flow batteries or sodium-sulfur (NA-S) batteries for stationary applications totaled 0.5% of the market (Pillot, 2017).

Asian countries account for the majority of global battery production: 95% overall, with 53% coming from China, 17% from South Korea and 20% from Japan (Pillot, 2017). Asia is also dominant in producing battery materials (metals, cathodes and precursors notably) and recycling equipment. As a consequence, these countries have an integrated industry covering all segments of the value chain, with secured supplies and economies of scale. While the EU represents an important and growing market for LIBs, European companies only hold a minor share of the market so far.

Recycling has become a widely-discussed topic in the context of the low-carbon energy transition, which is not only about shifting to a new energy system with a reduced or even neutral environmental impact, but also includes the larger considerations of the sustainability of economic development models. Through the promotion of the circular economy, a model “that harmonizes economic growth with environmental protection” (Lieder and Rashid, 2015), the reuse of end-of-life resources is strongly encouraged. Yet, a fully circular economy remains a myth. According to Jean-François Labbé, recycling will never achieve 100% recovery of all the resources contained in waste because of their degradation. Furthermore, in an economic system based on growth, recycling will never be the sole solution for supplying our society with all of the materials it needs (Labbé, 2016). Access to primary materials will always be necessary, but secondary sources could still represent a considerable amount of supply. By allowing the collection and treatment of potentially polluting and environmentally damaging products such as batteries (lead and cadmium are among the most polluting metals), recycling could not only prevent pollution but also partly compensate for the scarcity of mineral resources. As such, recycled materials might represent a strategic stock that would be used to reduce the vulnerabilities of the EU concerning raw material supplies.

This could also lay the ground for a new European industry that would allow the creation of 12,000 to 15,000 jobs in 2040 (2,000 to 3,000 in 2030). Between €400 and 500 million of materials could be recovered yearly in 2030 at current prices (including aluminum, cobalt, nickel and lithium) and up to €2.6 billion worth by 2040. Finally, recycling should also lead to the reduction of carbon dioxide emissions, as recycling is less emitting than the production of primary materials (Drabik and Rizos, 2018).

For these reasons, recycling is the third pillar of the EU's supply strategy called the "Raw Material Initiative (RMI)", alongside a "fair and sustainable supply of raw materials from global market" and a "sustainable supply of raw materials within the EU" (CE, 2008). In December 2019, Maroš Šefčovič, Vice-president of the European Commission, even announced the implementation of environmental standards for the importation of batteries, within the framework of the European Green Deal. These standards will affect the whole supply chain of batteries, from the sustainability of raw material extraction to the energy used for their manufacture and recycling.

However, the recycling of LIBs comes with several challenges for the EU. To give just one example: about 36,000 tons of cobalt were used in all types of batteries in the EU in 2017, with EVs representing only one sixth of this total.[2] As 12,000 tons had reached their end-of-life, only a 10% share (at best) was recycled in the same year. The exact number of batteries reaching their end of life being unknown, it is difficult to get a precise number of collected and recycled batteries. However, the European Commission (2019) estimated that in 2016, 36,950 and 37,956 tons (totaling 74,906 tons) of batteries were brought to the market for portable applications (electronics) and for industrial applications (automotive and stationary storage) respectively.

This paper will present the issues and challenges related to the recycling of LIBs and outline how to develop a European recycling industry. It starts by providing an overview of the different kinds of batteries, their specific uses and the technical characteristics of the recycling processes. The paper then addresses the potential of European "urban mining", before discussing the challenges and perspectives for the European battery recycling industry.

2. Calculation taken from the PhD research of the author about a material flow analysis of cobalt in the EU, based on trade data from Eurostat.

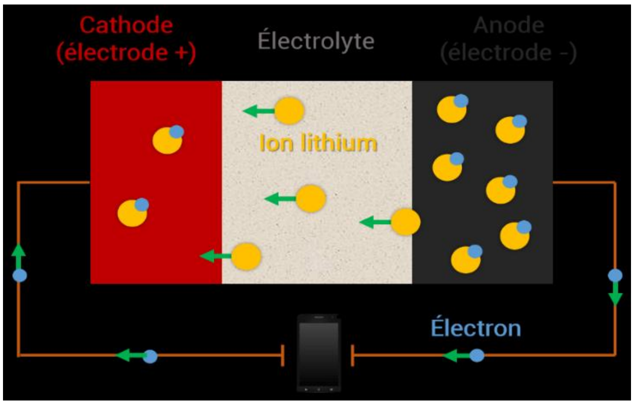
Lithium-ion batteries will dominate the recycling industry

Despite their important market share, lead-acid batteries are not covered in this study. However, they will be used as examples to illustrate some arguments which are also valid in the case of LIBs. This first part of this study focuses on the chemistry of batteries and so derives consequences for their applications and their recycling potential.

Different batteries for specific applications

A battery is formed by three elements, two electrodes (one positive and one negative) and one electrolyte. The positive electrode is called the cathode and it is made up of different elements (cobalt, nickel, aluminum, manganese, etc.), and some lithium. The negative electrode is an anode, manufactured with graphite because of its particular properties: chemical neutrality, thermal resistance and thermal and electrical conductivity. The electrolyte is formed by a lot of lithium ions whose proper circulation guarantees the battery's functioning. Anodes and electrolytes have a similar composition, compared to the cathode which can have different chemistries. LIBs were preceded by two principle types of batteries, which are still used, but with declining market shares.

Figure 1: Functioning of a lithium-ion battery



Source: T. Mathurin, 2013; © Ombelliscience 2018.

- Nickel cadmium battery (NiCd): the EU has forbidden these, considering cadmium as a toxic eleent, except in specific systems (Battery Directive 2006/66/EC). Despite their declining market (0.5%), they are still used in emergency industrial and aeronautic systems. The average content of NiCd batteries is 40% iron (Fe), 22% nickel (Ni), 15% cadmium (Cd), 1% cobalt (Co), and 15% other elements, including plastic (Vassura et al, 2009).
- Nickel metal hybrid battery (NiMH): they are used for PHEV (64% of their use, the remaining 34% being used for portable applications; Pillot, 2017). The average content of NiMH batteries is 33% nickel, 30% of iron, 10% rare earth elements (REE), 3% cobalt, 1% manganese (Mn), 1% zinc (Zn) and 22% of other elements, including plastic (Vassura et al, 2009).

There are several existing technologies for LIBs, with several chemical compositions for different applications, providing different levels of power and energy density.[3] Typically, EV batteries have a high level of power and energy density, so that cars can accelerate fast and drive long distances.

- Lithium-cobalt oxide (LCO) batteries have a high energy density but limited power and lifespan due to their lower cyclability. They are useful for portable applications as in small electronic appliances but are not adapted to transport. They are also prone to thermal instability, which can lead to accidents.[4] LCO batteries are generally made up of 22.8% Co, 2.7% of lithium (Li), 0.2% Ni and 8% copper (Cu).[5] Their high cobalt content is also an issue because of rising prices and the political instability in producing countries (Buchert et al, 2011).
- Nickel-cobalt-aluminum (NCA) batteries have high energy and high power densities. This makes them perfectly adequate for EVs and E-bikes. The cathode contains 86g of Ni per kilo, 16g of Co, 13g of Li and 2.5 grams of aluminum (Al) (g/kg of battery). Copper, aluminum and stainless steel are also part of the battery and module housing represents respectively 50g, 30g and 271g (g/kg of battery). NCA batteries manufactured by Panasonic are used by Tesla for example (Buchert et al, 2011).
- Nickel-manganese-cobalt batteries (NMC) also have high energy and power density. As such, they are planned to be used mostly in

3. Power density is the amount of energy that can be delivered in a given period of time, affecting how fast a vehicle can accelerate. Energy density is the capacity to store energy, affecting the range a vehicle can travel (Canis, 2013).
4. Example: the fire of an LCO battery on a Boeing 787 (Happich, 2013).
5. This is a rough estimate, as there is a lot of variation.

automotive applications. Their cathode is constituted of 39g of Co and Ni, 36g of Mn and 14g of Li (g/kg of battery). In the battery and module housing, there is 13g of copper, 1.4g of Al and 213g of stainless steel (g/kg of battery; Buchert et al, 2011).

- Lithium-iron-phosphate (LFP) batteries are characterized by a low energy density but high power. However, their low discharging rate makes them ideal solutions for E-Buses or heavy trucks. 460,000 E-Buses are in circulation globally, most of them in China (IEA, 2019). Their cathodes are composed of 7.6g of Li, 61g of Fe and 34g of phosphorus (P). There are also 38g of Cu, 13g of Al and 306g of stainless steel in the battery and module housing (g/kg of battery; Buchert et al, 2011). Chinese companies (CATL-BYD) hold the largest market share thanks to an early interest in this technology, but also due to the acquisition of foreign assets, like the purchase of the US company A123 Systems by Wanxiang Group in 2013 (Mathieu, 2017).

In 2016, the cathode market was dominated by LFP sales (36%) followed by LCO (21%), NMC (26%), NCA (9%) and LMO (8%). Avicenne energy forecasts the following market shares by 2025: 21% for LFP, 12% for LCO, 54% for NMC, 12% for LCA, and 1% for LMO (Pillot, 2017). For its part, the IEA scenario does not take LFP batteries into account but envisages a 10% share for NCA, 40% for NMC 6-2-2, and 50% for NMC 8-1-1 (IEA, 2019). As mentioned above, the use of cobalt is a challenge for all battery manufacturers both in terms of cost and responsible sourcing. That is why they are trying to reduce the quantity of cobalt contained in the batteries. Tesla plans to reduce the use of cobalt in its batteries within the next year, whereas NMC manufacturers want to build 8-1-1 batteries (80% Ni-10% Co and Mn), instead of the current 6-2-2 or 5-3-2.

Changes in the battery stock composition will be challenging

Over the next few years, new technologies should appear like lithium-titanate-oxide (LTO), currently being experimented on EVs and E-bikes by Mitsubishi and Honda (Dongjoon and Xingcheng, 2015), nickel-zinc batteries for heavy vehicles (Parker et al, 2017) or redox flows, vanadium technologies and lithium-silicon technologies for stationary applications (Le Cras and Bloch, 2016), titanium-niobium-oxides developed by Toshiba as the next generation of LIBs, or even the lithium-sulfur batteries for space applications (Toshiba, 2017; Nestoridi and Barde, 2017). However, all these technologies suffer technical problems which only make them available for niche markets.[6]

The most promising large-scale developments are related to the All-Solid-State-Battery (ASSB) using lithium-metal and made with a solid electrolyte and a lithium anode. The use of new active materials should allow increased capacities, voltage and density for the battery, just as the inorganic state of the electrolyte should increase its safety and reduce inflammability. Free from such problems, it should be possible to remove the fire safety systems, which would reduce the mass and the cost of the batteries. However, even if this technology should replace the current ones, it is unlikely to be commercialized for mass consumer markets before 2025-2030.

Lithium-ion batteries remain the future of the recycling industry. So far, NiMH and NiCd batteries have constituted the majority of recycled batteries because of their use in hybrid vehicles. However, given the growing sales of EVs, the composition of the stock is changing and LIBs will soon overtake their predecessors. Yet this observation raises some questions. Their different chemical composition will be a key element in their recyclability. Currently, and considering the recent tendencies of metal prices, recycling a battery without cobalt or even nickel, like a LMO (lithium-magnesieum-oxides), will be far less profitable. Furthermore, the different chemical compositions are sources of incidents and involve different processes, especially by hydrometallurgy, which in turn increases costs. Finally, the composition of a battery leads to different uses, directly linked to their recycling. Indeed, electronic applications, which still represent the majority of LIBs in circulation, are less easily collected and recycled.

A major challenge stems from the need to optimize battery standards and sourcing, to allow for optimal collection, knowledge of their chemistries and cost-effective recycling process, which will require automation and large scale processes to reduce costs.

An overview of the recycling processes

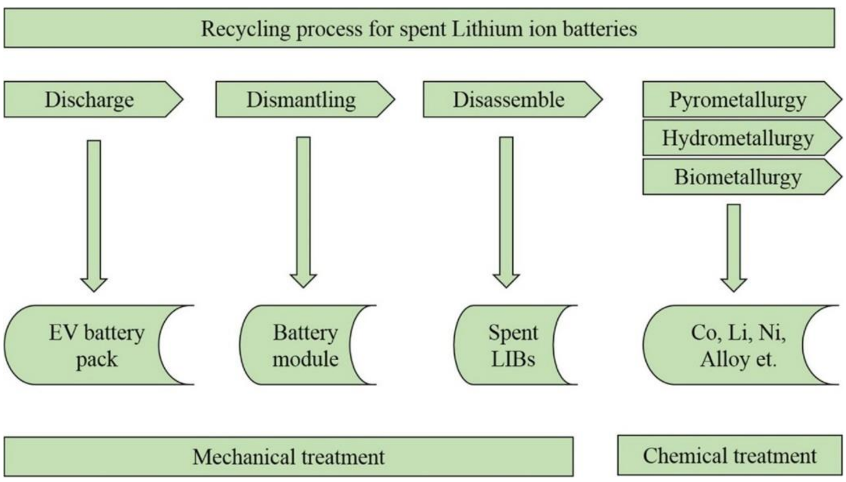
Recycling is one of the four to six main life stages of a metal, following the other processes of extraction, transformation, manufacturing, usage, and finally eventual collection for waste management (Chen and Graedel, 2012). While recycling allows elements to be recovered within a circular

6. Li-S batteries suffer from the accumulation of layers on the anode and a poor cycling performance, whereas the disadvantage of lithium-titanate batteries lies in their lower inherent voltage, which leads to a lower energy density than conventional lithium-ion battery technologies.

economy framework, it also uses resources such as energy or chemicals for treatment processes, but much less than are used in new production: in the case of aluminum, copper and iron, recycling even allows saving respectively 95%, 85% and 74% of the energy that would have been used to extract anew the same quantity of metal (Cui and Forssberg, 2003). A closed-loop process for batteries would cut out 51% of the environmental impact of their manufacturing process (Dewulf et al, 2010). By implementing a closed-loop system, materials can be recovered and reused in the same application as before, which is an interesting perspective in environmental, economic and strategic terms. It is also possible to build an open-loop system, whereby materials are recovered to be reused in other applications.

Once waste is collected, the recycling process may include the following stages: shredding, disassembling, incineration or acid treatment for the separation of the elements and their recovery. According to the Joint Research Council (JRC), four phases can be implemented for the recycling of LIBs (Lebedeva et al, 2017): mechanical, pyrometallurgical (pyro-process) and hydrometallurgical (hydro-process) treatment, the fourth one being a thermal pretreatment, followed by a hydro-process (combination of pyro and hydro-process). A biometallurgical process using micro-organisms, which allow to recover insoluble substances under an aqueous form, is also available. The recovered elements can then be separated through other processes. If this consumes little energy, the method needs more time than traditional ones, and only works with low concentrations of recyclable material. Such methods are not yet usable on a large scale.

Figure 2: A comprehensive process of recycling lithium-ion batteries from Evs



Source: Yun et al, 2018

The mechanical phase includes three steps, from discharging the battery pack, dismantling the battery module and disassembling the spent LIBs. After that, two processes are possible.

The pyro-process refers to incineration at very high temperatures, which eliminates organic elements (the carbon anode) and the separator (polymers). This leaves a powder of nickel-cobalt alloys which are then treated chemically. The process is criticized because of its high energy consumption and because of the loss of lithium and aluminum in the slags (Meshram et al, 2014). Furthermore Ni-Co alloys need to be re-treated to obtain Ni-Co sulfates, in order for reuse in batteries. However, one key advantage of a pyro-process is that it avoids the shredding-dismantling phase. Everything burns, which means that some energy recovery is also possible as organic material to fuel furnaces.

The hydro-process includes a mechanical treatment for shredding and disassembling batteries. After that, they are put in an acid solution for the separation of elements. Even if the liquid solution is almost directly usable for the fabrication of Ni-Co sulfates, and even if the separability of these two elements is difficult due to their similar physical properties, some elements like lithium or copper might be lost. Furthermore, there is a need for a specific hydro-process for each type of battery, in order to avoid negative chemical reactions. The shredding-dismantling phase generates a loss of materials and raises safety issues as well, depending on the remaining charge of the battery. If a battery is still charged, it can explode while being shredded. Finally, the cost of solvents and their environmental impact are two additional problems linked to hydro-process.

A combined pyro-hydro process may be preferable for two reasons. First, pyro treatment avoids the disadvantages linked to safety issues stemming from the different chemical composition of batteries, their constitution and their state of charge. Hydro-treatment can then logically be used in the separation and the treatment of the different materials recovered in slags, with different materials being susceptible to treatment, using different kinds of chemicals and acids.

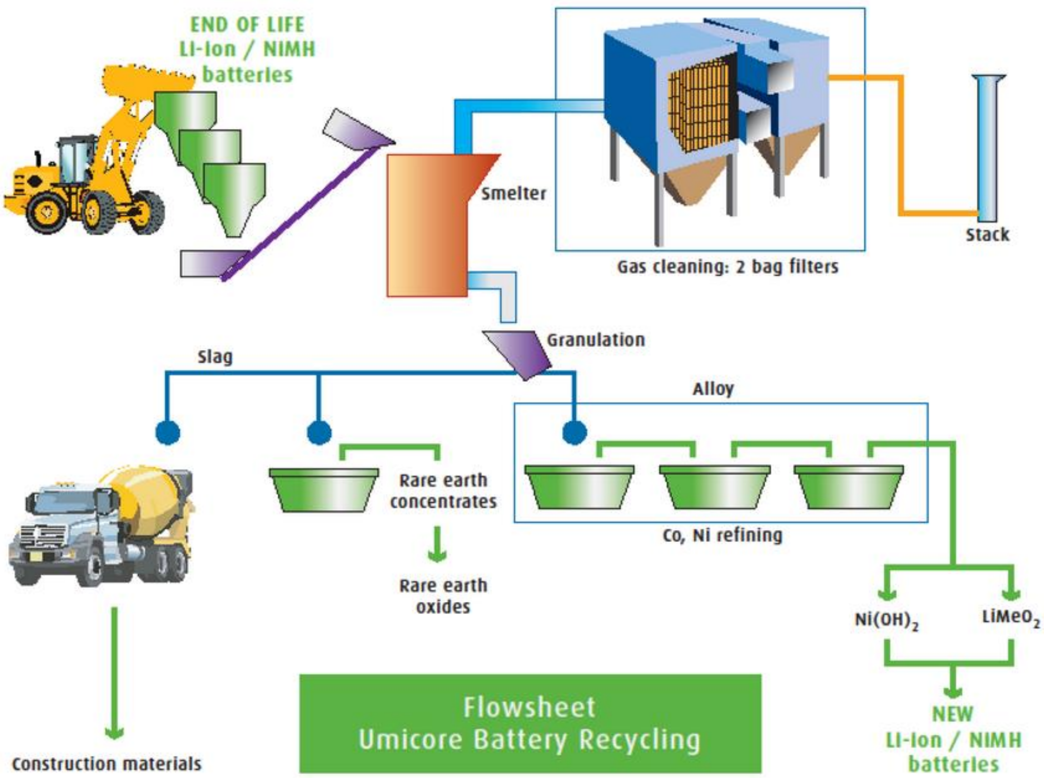
In 2013, the ELIBAMA project (European Li-ion battery advanced manufacturing for electric vehicles; 2013) listed about seven different technologies for the recycling of LIBs, using alternatively either pyrometallurgy or hydrometallurgy. A brief presentation of the three technologies highlights their operational lifespan (the Toxco and Sony-Sumimoto processes) and their originality (Umicore):

- The patent for the so-called Toxco process was filed in 1994 in the United States. It uses a preliminary cryogenic treatment with liquid nitrogen (at -195°C) which reduces the material reactivity. The batteries are then crushed and treated with an alkaline solution to recover lithium salts.

- The Sony-Sumimoto technology was launched in 1996. It includes two main steps, the incineration of the batteries at 1,000°C, and the cobalt extraction. Residues of iron, copper and aluminum can be found in the ashes and separated magnetically (Lupi et al, 2005).
- The Umicore process uses a combined pyro-hydro treatment for the batteries. They are burnt yielding two kinds of products: an alloy containing valuable metals like cobalt, nickel and copper, designed for a further hydro-process; a slag containing lithium which can be used either in the construction industry or processed to recover the lithium (Umicore, 2019). This process can lead to a recovery rate of 95% for cobalt, nickel and copper just as additional quantities of lithium.

If the recycling process is deficient, companies will not gather sufficient quantities to allow economies of scale, which will reduce the profitability of investments.

Figure 3 : Umicore recycling process



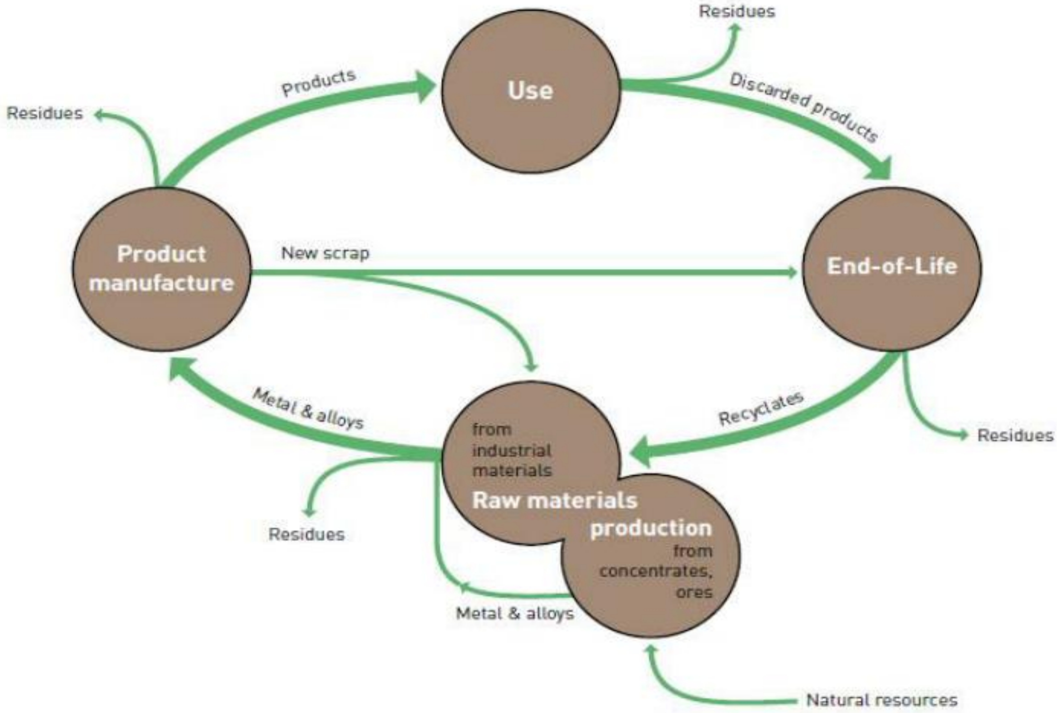
Source: Elwert et al, 2015.

Key challenges for material recovery: the value of the recycled materials and structuring the collection system

The recycling industry for batteries faces three main economic and technical challenges: the first is design complexity, due to the numerous metals needed to manufacture a product (60 of them for example are necessary for a smartphone), as well as their low quantity and concentration. These properties are a challenge for the technical ability of recycling, and are one of the reasons that recycling is hardly profitable. Secondly, important quantities of end-of-life products have to be collected and recycled at a critical scale to achieve profitability. If the collection system is deficient, companies will not gather sufficient quantities to allow economies of scale, which will reduce the profitability of investments. A third challenge relates to the value of the metals, which depends on the supply and demand balance and also on the local conditions where they are mined.

These challenges will be assessed with a brief overview of the cobalt, nickel and lithium markets and basic modeling of European urban mining.

Figure 4: The life cycle of a metal, the loss of residues at each stage and the reuse of scrap



Source : Meskers et al, 2008

Two factors affecting metal prices: local situations and the supply/demand balance

So far, the profitability of battery recycling has been closely linked to the prices of cobalt, and to a certain extent, to the situation of the nickel and copper markets. For example, elements contained in LMO batteries (without cobalt) had a value of $860 per ton, whereas materials contained in LCO batteries were valued at $8,900 per ton in 2014 (Wang *et al*, 2014). But prices of cobalt tend to be volatile. In April 2018, a ton of cobalt sold for about $95,000, but only for $24,000 the following year (infomines, 2019). By mid-2018, prices had increased strongly due to uncertainties regarding the political situation of the Democratic Republic of Congo (DRC) but also on account of the growing consumption of battery materials which generated a disruption of the market structure and some production bottlenecks, linked to both mining and refining production capacities.[7] Originally, cobalt was used in chemicals for pigments and in superalloys for

7. According to Darton commodities (2019), 72% of the mined cobalt came from the DRC in 2018, whereas 65% of refined cobalt came from China.

aircraft engines. While only 34% of cobalt was produced for the battery market in 2009 (Roskill, 2017), this figure reached 54% in 2018 and is rising (Darton commodities, 2019). Simultaneously, production nearly quadrupled between 2000 and 2018, from 32 kt to 140 kt (Shedd, 2002; 2019). Refined production has also shifted from cobalt metal to cobalt chemicals, as cobalt sulfate is used for manufacturing batteries. The opening (or re-opening) of new mines in the DRC, of new refining facilities in China as well as a less dynamic EV market than predicted (as seen in China) brought prices down. Yet they could rise again in the medium term because of, among other things, the decision by Glencore (the world's largest cobalt producer), to close temporarily the Mutanda mine for care and maintenance, one of the largest mines in the world (Nedelec, 2019). Also, prices are expected to rise due to battery fuel cell demand from European car makers.

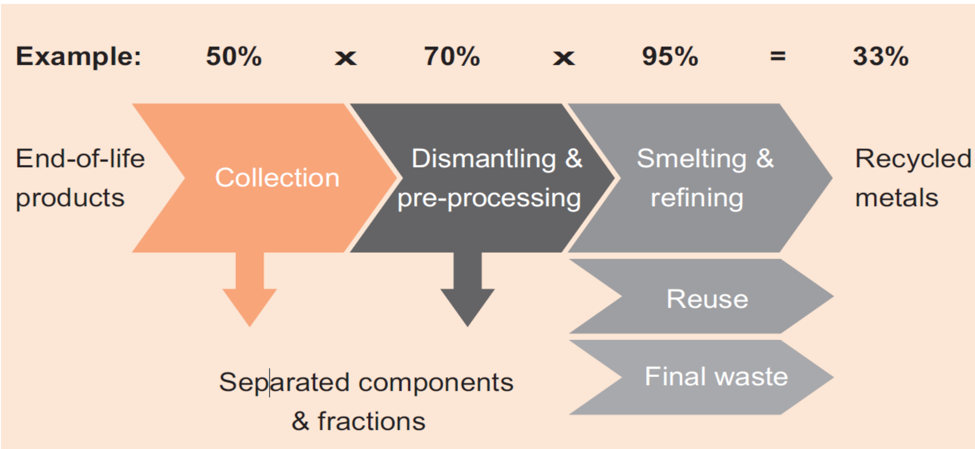
The volatility of cobalt prices has prompted battery manufacturers to use less of it in cathodes. The best example is the NMC 5-3-2 or 6-2-2, which will switch to 8-1-1 and less, if possible, in the next few years. But if cobalt constitutes the incentive for the industry to recycle LIBs, putting less cobalt into cathodes could endanger the profitability of the whole recycling chain. According to Christian Hagelücken, the decrease could be compensated by the recycling of nickel. While 70% of global nickel production is used for stainless steel, only 3% is used for the manufacturing of batteries. However, this segment will grow strongly in the years to come, due to increasing use of nickel, and market tensions may increase due to the lack of production capacities for nickel sulfates (Nickel Class I), a vital component of batteries (Legleuher, 2018). From this perspective, closed-loop recycling of nickel should gain in value, and eventually compensate for the lower recovery of cobalt.

Lithium is the least recycled of the three metals (less than 1% as cobalt and nickel have recycling rates of respectively 16% and 32%; Coulon *et al*, 2015). Current prices are too low to make it profitable and lithium reserves are large and located in rather stable countries (Schmidt, 2017), which limits the political risk factor in price formation.

The limits and opportunities of the "urban mines"

The expression "urban mining" is part of a much larger debate about the supplies of raw materials, sustainable development and the circular economy. As such, it includes all activities and recovery process of components, energy or elements coming from products, building or waste generated by human activities in an urban framework. As "recovery" means "reuse" or "recycling", it is important to understanding for the latter, the different terms used to calculate recycling rates. The end of life recycling rate (EoL RR) represents the recycled quantity of a given product in comparison to the waste generated by this product. A complementary concept is the end of life collecting rate (EoL CR), referring to the quantity collected of a given product, in comparison to its generated waste. Finally, the efficiency of recycling processes is calculated based on the recycled quantity, compared to the recyclable quantity actually available for recycling in a product or in a flow of products (PR, processing rate; RER, recycling efficiency rate; Talens-Peiro *et al*, 2018). For example, the EU generated about 10.4 million tons of waste of electric and electronic equipment (WEEE) in 2013 (with 11.4 million tons expected in 2020; Arda et al, 2018). But 50% of waste was in fact lost during the collection phase. As a 100% recycling rate for all the elements contained in a product is impossible, the conclusion is that more than 50% of the materials contained in WEEE in the EU are presently lost.[8]

Figure 5: The main steps of a recycling process chain



The overall recycling efficiency is the product of single step efficiencies (fictitious numbers here).

Source: Hagelücken and Grehl (2012).

Research shows that the battery collecting rate fluctuates between 5% and 15% globally for small electronic appliances, and around 80% for electric vehicles (Blandin, 2016; Graedel *et al*, 2015), even if this last number is rather hypothetical given the low number of vehicles that have reached their end of life.

8. There are other parameters like the old scrap ratio (OSR) or the recycled content/recycling input rate (RC/RIR) but as these help to calculate the overall recycling rate for a given metal or product, they are not useful for our study.

Thanks to the EU Directive on end-of-life vehicles (Directive 2000/53/EC), a reuse and recovery target has been set: 85% of each vehicle should be reused or recycled, and 95% should be reused or commercially exploited in 2015. Therefore, a fair assumption is that the collection, recycling and recovery rates are significantly higher for EV batteries than for small electronics. Furthermore, EVs represent only a (growing) fraction of the whole number on batteries put on the market.

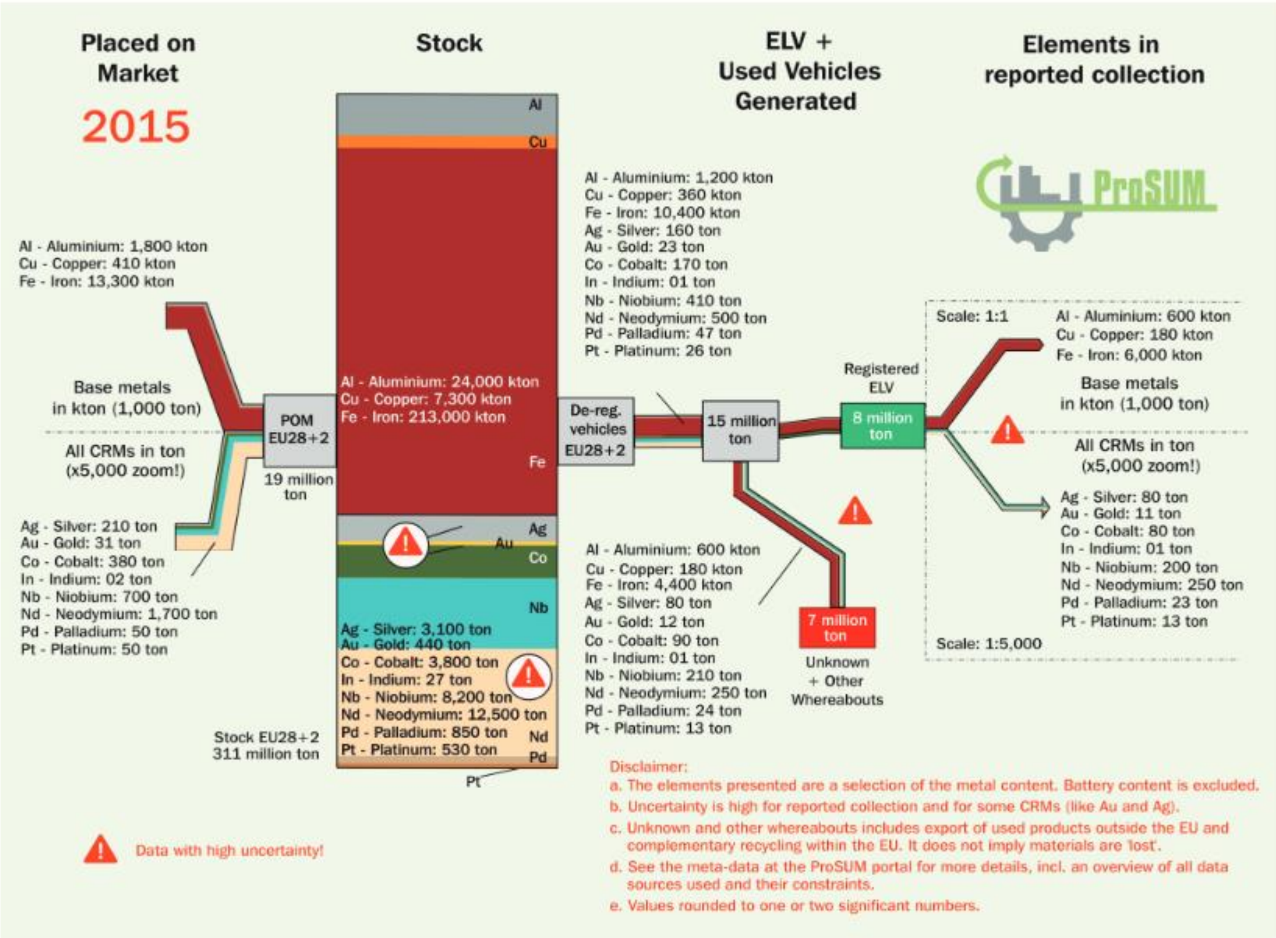
With EV sales growing, they will become a major resource, but only after they have reached their end of life in about ten to fifteen years. If nowadays, the challenge is more concentrated on the collection and the recycling efficiency of small electronics, some questions remain about the efficiency of legislation. In 2017, the French Agency for the Environment and Energy (ADEME) recognized that, despite a positive structuring of the sector, the number of ELVs (End-of-life Vehicles) is still unknown (even if it could be calculated), while only 50% of vehicles are processed in an authorized network. The remaining 50% are neglected, exported (most of the time illegally) or poorly recycled (Monier *et al*, 2019).

The ProSUM project (Prospecting secondary raw materials in the urban mine and mining waste) aims to determine the quantity of secondary resources in the European urban mine. Waste types are divided in three categories (batteries, electronic & electric equipment, and vehicles) and twelve metals (cobalt, lithium, manganese, copper, gold, neodymium, indium, silver, aluminum, iron, platinum and palladium) are covered in the final report. The 2019 study considers that 2.7 Mt of batteries were brought to market in 2015 (85,000 tons of LIBs), with a stock of 9 Mt (250,000 tons of LIBs), while waste represented 2 Mt, of which 88% were lead-acid batteries. Out of the remaining 400 kt, the share of LIBs is only of about 22.5% (90 kt), containing 2,700 tons of cobalt and 720 tons of lithium. Only 12.9% (350 tons) of the cobalt and 9.7% (70 tons) of the lithium has been collected, which does not even correspond to the recycling rate but rather to the collecting rate (Huisman et al, 2017).

In China, it has been estimated that less than 40% of the materials contained in a battery can be recycled given the current organization of the battery life cycle, meaning that 70% of the nickel, 67% of the cobalt, 77% of the lithium and 95% of graphite were lost in 2016 (Song et al, 2019).

The following ProSUM figures illustrate the flows of waste and metals collected or lost.

Figure 6: Stocks and flows of metals in vehicles in the EU28+2 in 2015, in kt (thousand tonnes for base metals) and tonnes for CRMs

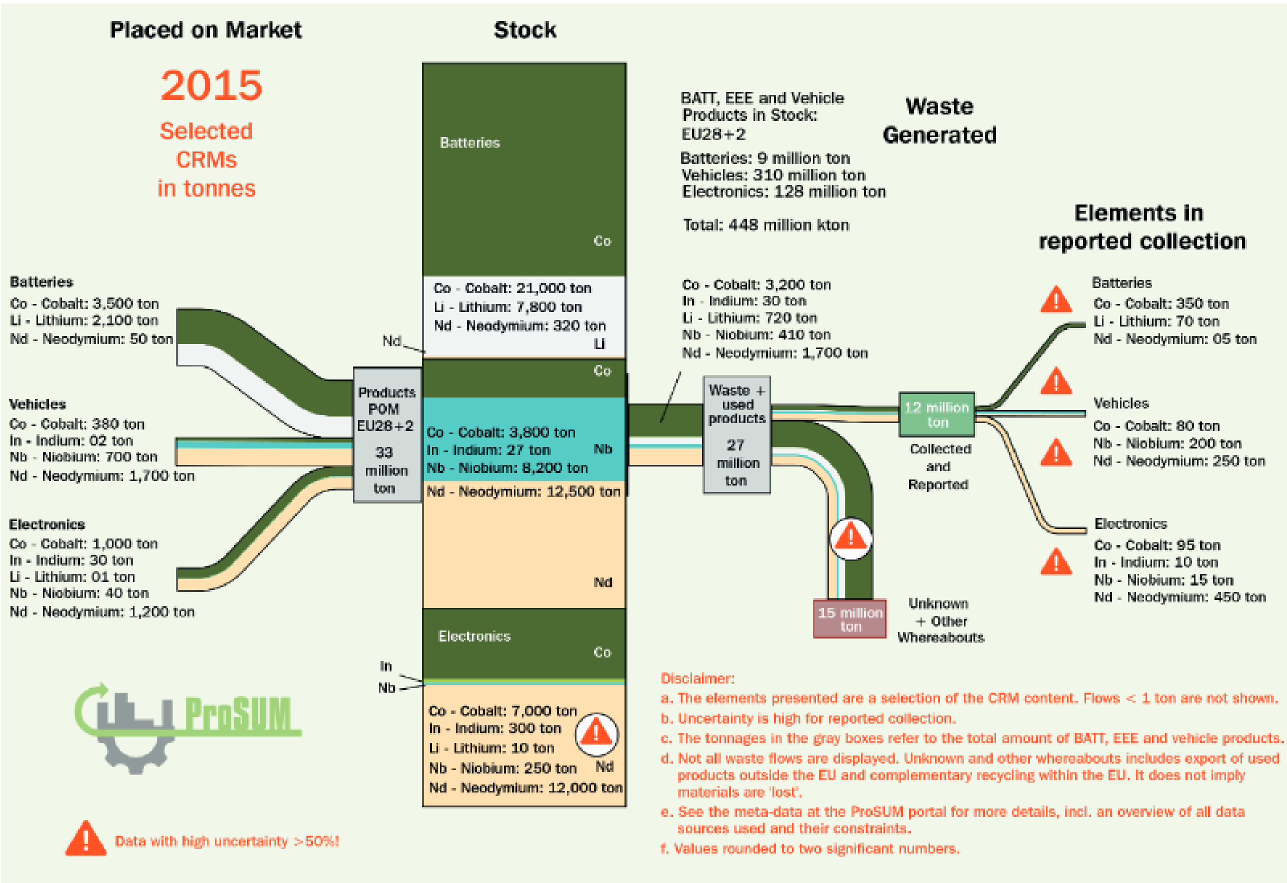


Source: Huisman et al, 2017.

Apart from the difficulties of setting up an efficient collection system, legal or illegal exports of waste are another challenge for the EU recycling industry. Exported as waste or as second hand products, these exports represent a loss for the European economy. The report Countering WEEE Illegal trade estimates that two thirds of the WEEE collected in the EU were exported in 2014, half of them illegally, equal to 3.15 million tonnes (Huisman et al, 2015). In 2017, 80% of WEEE exported in the world were still poorly documented, or not documented at all (Baldé *et al*, 2017). Now, there is no guarantee that exported waste will be recycled, and if so, it may still not be in sanitary and environmentally suitable conditions. In fact, such waste is often recycled for precious metals or copper through informal networks.

While collection is an issue, it needs to be asked what would happen if there were not enough industrial capacity of battery processing. Presently, there are no clear numbers about the battery treatment capacity. A study by the Joint Research Center of the European Commission in 2016 estimated European recycling potential capacity at about 40,000 tonnes. However recycling of NiMH, NiCd and alkaline batteries were also taken into account (Lebedeva *et al*, 2016). In a more recent study, European capacity was estimated at 15,000 tons (CSF, 2019). At the world level, Hans Eric Melin, consultant in lithium-ion battery life cycle management, reckoned that 97,000 tonnes of batteries had been recycled in 2018, including 67,000 tonnes in China and 18,000 tonnes in South Korea, with the reminder covered mainly by the EU. Most of the expansion projects are located in China, and should reach 400,000 tonnes in 2025. However, that will not be enough, considering that 800,000 tonnes should reach their end-of-life in the same year (Melin, 2019).

Figure 7: Sankey diagram for market input, stocks, waste generation and waste flows for selected CRMs, 2015, EU28+2



Source: Huisman et al, 2017

The European industry in the battery value chain: inventories and perspectives for recycling

If batteries are recycled in a closed loop, it means that the resulting recycled materials are re-used for the fabrication of new battery materials. This requires having the relevant industrial capabilities but also markets, to make the operation profitable. An integrated industry is capable of activating and managing its different segments and by doing so, achieving economies of scale by rationalizing the use of infrastructures and processes, which in turn can sometimes be used variously in several segments of the value chain. It would also be a token for industrial sovereignty.

However, there is no universal model for such organization. If Chinese companies are often vertically integrated, sometimes from the mine to the battery, other solutions are also available: for example, a horizontal organization for the European industry, made up of several companies mastering one to three segments of the value chain and cooperating together through formal or informal arrangements. The goal here would be the creation of an integrated European battery industry, directly linked to a European market.

The disintegration and re-integration of value chains

While vertically integrated companies, controlling all or most of the value chain, were considered the norm before globalization, a disintegration of industrial value chains has taken place since the 1980s, amplified by globalization. Companies have concentrated on their core competencies and have given up, or externalized, less valuable activities in countries with better comparative advantages. This phenomenon was corroborated by David Humphrey for the mining industry. After decolonization, most mining industries in newly independent countries were nationalized, leading to the creation of large integrated industries, from extraction to transformation. With prices falling at the end of the 1970s, debt grew to unsustainable levels and structural adjustment politics were launched, leading to the separation and selling of mining assets (Humphreys, 1995).

However, the economic progress of developing countries since the beginning of the 21th century has fostered competition for the control of mineral resource supplies. Two steps can be identified: the creation or the taking of control of national value chains in different kinds of activities, followed by their integration. Countries with mining assets can implement a strategy to develop their industries and their infrastructures, with the objective of manufacturing products with higher added value. For example, the DRC banned the export of cobalt ores and concentrates in 2013. Even if it exports some primary products and even if part of the Congolese production is still illegally exported, the country now exports more value added products like cobalt oxides and hydroxides or some alliage-blanc (Darton Commodities, 2019). In 2018, the government also introduced a special tax on “strategic minerals”, including cobalt. However, the lack of transport and energy infrastructures, as well as corruption issues are serious hurdles to this strategy. In 2014, Indonesia implemented an export tax on nickel ores and concentrate exports, in order to develop its downstream production. In 2017, this measure was replaced by export quotas because of the decreasing prices of nickel. However, its goals were partly achieved as the country induced the construction of several refineries by Chinese companies, which are dependent on Indonesian nickel (Legleuher, 2018). Another example is Bolivia which negotiated the exploitation of lithium at Uyuni with foreign companies, in exchange for the opening of battery precursor facilities.

The best examples of setting up a full value chain are found in China, whose strategy on rare earths allows it to have a monopolistic or near monopolistic position in every segment of the value chain, even for research and development. But this strategy is also observable for the battery industry. The share of the market held by Chinese companies for their manufacturing (53%) has already been mentioned. Some of these countries are also leaders in the production of EVs like BYD. Their strategies extend to resource activities as well. Firms like Jinchuan, Huayou Cobalt or China Molybdnenum control more than one third of the cobalt mining production through investment in the DRC, but also in Papua New Guinea and in New Caledonia. Furthermore, 60% of the refined production takes place in China. The same is happening for lithium, where two Chinese companies (Tianqi Lithium and Ganfeng Lithium) control 60% of mining assets and 50% of refined production (Bonnet et al, 2019). While China still held 55% of nickel production in 2016, its share had decreased from 80% in 2013 (Legleuher, 2019) and it imports 40% of refined nickel production (Class I), although it has most of the world's production capacity (INSG, 2019). Other companies like the GEM Group have important capacities in LIB recycling (300,000 tonnes; GEM, 2019) but also for the production of battery precursors. The company also has a subsidiary (Jiangsu Cobalt Nickel Metal Co. Ltd or KLK) which is the second largest producer of cobalt oxide and owns mining assets in the DRC.

It would be pointless to make an inventory of the whole Chinese battery value chain. However, it is interesting to note that through strategic investment policies and the construction of an integrated value chain, Chinese companies have access to all the needed technologies and are leaders in every segment of the LIB industry.

The industrial structure of the European battery value chain

The battery value chain concerns not only batteries, or even EVs manufacturing, but also the ability to produce, refine, assemble and recycle the elements contained in it.

The EU mining industry has some limited but also some promising capacities. Spain and Portugal produce some lithium for the glass and ceramic industry. New deposits are opening in Portugal, even if there is no refinery project at this time. Advanced exploration is also taking place in Finland (Keliber project), Germany (Zinnwald project), as well as in Serbia (Jadar project) (Gourcerol, 2019). As for cobalt, 2,300 tonnes are produced annually in Finland, and the EU is a key actor in refining production (15% of global output, including 11% at the Kokkola refinery in Finland). Exploration is ongoing in Slovakia, Sweden and Finland (Alves Dias et al, 2018). European nickel production represented about 9% of world output and 6.5% of the mined and refined quantities in 2017 (occurring in France, Finland and the United Kingdom; EC, 2017). In Finland, Terraframe plans to operate a deposit for the production of nickel sulfates. However, due to the non-existence of a European chain in battery manufacturing, this project is still pending.

The automobile industry plays a strong role in the European economy. In 2017, it represented 13.1 million jobs and 6.4% of the GDP (ACEA, 2018). If the EU accounted for 1.2 million of EVs in stock and 385,000 vehicles sold in 2018, European companies such as BMW (4th), Renault (9th), Volkswagen (10th) and Volvo (20th) are also among the most important EV manufacturers globally, with cars like the Zoe (Renault), the

BMW 530e or the BMW ie3 (Kane, 2019). While there is no player as big as in Asia, the EU battery industry employs about 30,000 people with a turnover of €6.5 billion and manages 16 R&D centers (Mathieu, 2018). However, the amount of batteries produced is rather limited (cell production capacity of 1,295 GWh in 2016 or a 2% of the global total) and the main targets are niche markets (SAFT in France or EAS Germany GmbH in Germany). Umicore (Belgium) and Johnson Mattey (United Kingdom) produced 15,100 tonnes (NMC-LCO) and 2,650 tonnes (LFP) of cathode materials in 2015, whereas BASF produced 200 tonnes of electrolytes in 2014. There is also some minor production of anodes (Denmark and Switzerland) and separator materials (Denmark). European companies tend to focus on the assembly and battery integration stages, which cannot be standardized. BMW invested about $100 million in its facility in Dingolfeng to design and develop its core electric drive components including power electronics: its battery management system (BMS) and the electric vehicle system. Renault has developed its battery pack (including the BMS) in close partnership with LG Chem, which provides the battery cells. Furthermore, several projects of battery gigafactories are under construction or planned in Europe.

In terms of recycling, European companies like Valdi (Eramet, France), Umicore (Belgium), Accurec Recycling (Germany) or AkkuSer Oy (Finland) have the capacity to process about 40,000 tonnes of batteries per year, even if they also recycle only NiMH and NiCd batteries. For example, Valdi does not recycle LIBs and it remains unclear if the Eramet battery processing project will happen inside Valdi, using its knowledge and infrastructures or in a whole new place with new subsidiaries (Lebedeva et al, 2017). New companies have set up facilities in Germany (Duesenfeld, Redux), in Austria (Neospace, Redux) and in Sweden (uRecycle), but there is no precise information about their capacities, nor about their processes or their products (Dallhöf et al, 2019). Smaller companies like G&P Batteries and AEA technology also exist in the United Kingdom, but we do not have information about their capacity (Lebedeva et al, 2017). In France, companies like SNAM and Eurodieuze own, for now, the market of EV battery recycling (this is particularly true for SNAM), even if, as small companies, they surely lack investment capacities for large scale recycling in the future. However, it is interesting to observe that there are two possible ways forward. Umicore, as an integrated company, recycles most battery parts in a closed loop system, using the recovered materials for the manufacturing of battery precursors. By contrast, SNAM recycles its batteries in an open-loop system, producing a so called “black mass”, an alloy sold to metallurgical companies. The same is happening for Valdi, which sells recovered nickel (in its metallic form) to Aubert & Duval (the metallurgical subsidiary of Eramet).

Table 1: Assessment of European capacities for battery recycling in 2019

Country	Company	Process	Capacity (tpy)	Product
Germany	Accurec	Mechanical, electric furnace	6 000 (e)	Co alloy, Li2CO3
Finland	AkkuSer and Boliden	Mechanical for copper refining by Boliden	4 000 (e)	Copper, black mass
Germany	Duesenfeld	Combination of mechanical and hydrometallurgical (LithoRec process based)	3 000 (e)	Co, Ni, Mn as active materials
Austria	Neometals	Mechanical and hydrometallurgical	Lab scale	Possible recovery of Co, Ni, Cu, Li, Gr
Germany and Austria	Redux	Mechanical and hydrometallurgical	10 000 (e)	Plastics, Fe, Cu, Al
France	SNAM	Pyrometallurgy	300 (e)	Black mass (Co, Cu, Ni)
Belgium	Umicore	Pyrometallurgy and hydrometallurgy	7000	Co, Ni, Cu chemicals
Sweden	uRecycle	Mechanical	na	Black mass
United-Kingdom	AEA Technology	Hydrometallurgy	na	na
United-Kingdom	G&P Batteries	na	na	na
France	Euro-dieuze	Hydrometallurgy	200	na
France	Eramet	Pyrometallurgy	20 000	Ferro-nickel/ Ferro-manganese alloy

Note: (e) = estimate ; na = not available

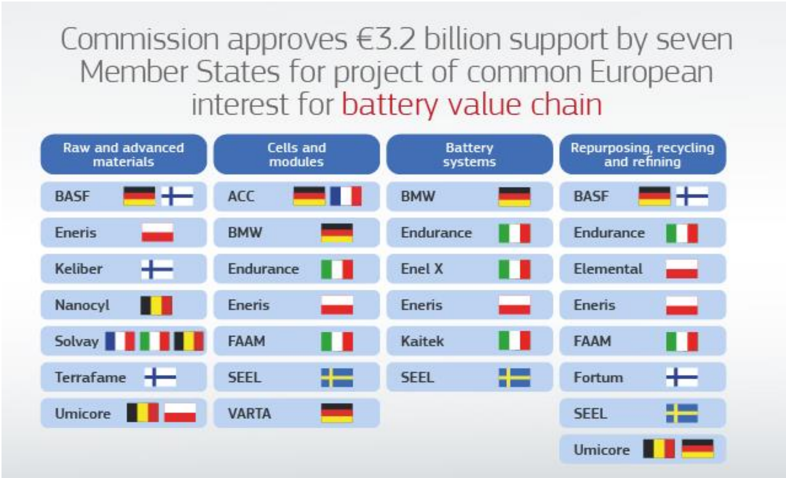
Source: Lebedeva et al, 2017; Dallöf et al, 2019; Lv et al., 2018; Neometals, 2019; Redux, 2019; Umicore, 2019; uRecycle, 2019

An alternative to recycling would be the re-use of batteries for other purposes like stationary storage. Called "second life batteries", this solution attracts a lot of interest but also faces some challenges. The market is not yet mature and perspectives are unclear, especially as flexibility needs can be covered by a wide range of solutions, including demand response, interconnectors, vehicle-to-grid technologies, etc. If stationary applications are expected to grow in the next years, it is still unclear whether lithium-ion or other technologies will be used. Re-use will also require investments in industrial plant to transform and integrate collected batteries for adapting them for their second lives. However, uncertainties over numbers, the state of batteries and their chemical composition remain for now economic obstacles to the large-scale development of capacity, which is costly to install. Several projects have been launched in Europe at the R&D level (Battery 2020, Energy Local Storage Advanced System or Elsa, AbattRelife, etc.); at the industrial level (BMW and Vattenfall, Renault and Connected Energy, Nissan and Eaton, etc.) or at the local level (2BCycled in the Netherlands or Nettficient in Germany). Toyota, Sumimoto and Hyundai also have their own projects. (Mathieux et al, 2017; EC, 2018; Hill et al, 2019).

The outlook for the European battery recycling industry

Acknowledging the dependence of the EU in the area of battery manufacturing, the EC encouraged the launch of the EBA and dedicated an additional €100 million to R&D projects. Member States are also contributing to this initiative, with for example France and Germany announcing financial support of €700 million and €1 billion respectively. The EBA should gather seven Member States (Germany, France, Italy, Poland, Belgium, Sweden and Finland), with a total of €3.2 billion in public funding, and an additional €5 billion in private investments until 2031. More than 80 partners including companies and research institutes have been identified and have joined the projects. The objective of the EBA is the establishment of a battery ecosystem in the EU, with the creation of industrial partnerships and pilot projects along each step of the value chain, focusing on: raw and advanced materials, cells and modules, battery systems and repurposing, recycling and refining. One of the main goals is to reach 200 GWh/year of battery manufacturing capacity in the EU in 2025, to meet the EV market needs. Comparatively, the LIB market should represent 278 GWh/year in 2025 (Pillot, 2017), which make the European project look very ambitious.

Figure 8: Example of participation in the EBA, by countries, companies and value chain segments



Source: European Commission

There is a consensus in the EU that the circular economy should be promoted, and several pieces of legislation have been adopted in this context: Directive 2000/53/EC for the recycling of end of life vehicles (ELVs); Directive 2006/66/EC for the recycling of batteries (lead-acid and nickel-cadmium); Directive 2009/125/EC about the Eco-design; Directive 2012/19/CE for the recycling of WEEE. These are completed by the action plan of the EU for the circular economy in 2015. However, if the battery directive stipulates a minimal 70% recycling rate for lead-acid and NiCd batteries, the rate for the total mass of LIBs is only of 50%. A revision process is ongoing but no concrete steps will be taken before 2021, and there are major divergences among stakeholders regarding how the new targets should be calculated (in terms of mass and elements).

According to Christian Hagelücken, the EU faces three big challenges for its battery industry and especially for the recycling segment concerning the collection of batteries, the revision of the directive, but also integrated cooperation between European shareholders throughout the value chain.

With regards to collection, several actions should be launched:

- despite limited results, awareness-raising measures aimed at consumers should be continued;
- a deposit system should also be put in place, to encourage the return of small electrical and electronic appliances (smartphones, notebook, tooth brushes, etc.);
- leasing systems based on more modular design (changing of batteries or software rather than changing entire smartphones, for example) would also be helpful.

The last two recommendations would allow the simplification of the collection and logistic chains while also being a control tool of illegal or second-hand exports. Indeed, if consumers are encouraged to give back their small electrical and electronic goods to vendors, the latter should be able to partner with recycling industries to process waste. Of course, this will imply changing business models. Similarly, if recycling incentives are sufficient, illegal or second-hand exports will not be profitable.

The revision of the directive should be based inevitably on the fraction mass of the batteries but should also include the following:

- the introduction of recovery rate quotas for battery materials (between 75% and 90%);
- the standardization of procedures for recycling plants through environmental and sanitary rules for good working conditions;
- the regulation of second-hand or waste exports (certificates of second-use and thereafter of their recycling in good conditions).

This should go hand-in-hand with efforts by European industry to foster cooperation and geographical integration to facilitate investments in infrastructures and technologies, including:

- recently, Umicore bought the battery activities of the Kokkola refinery from Freeport McRoan, which is close to Finland's nickel and cobalt mines but which also treats materials from Russia. This investment turns Umicore into an integrated company for the production of battery metals and materials (refining-transformation/production-recycling). Recently, Umicore also announced in 2018 its intention to build a new furnace for battery treatment with a capacity of 100,000 tons (Charlish and Shabala, 2018);
- French company Eramet also invested in battery materials and infrastructures. Originally, it produced nickel from its New Caledonian operations as well as a few tons of cobalt refined from nickel mattes. Nevertheless, the company also invested in lithium in Argentina and in battery recycling through its subsidiary, Valdi. The project ReLieVe that brings together Suez, BASF and Eramet is a two-year financed project by the EIT Raw Materials. Beyond being the first of its kind in the EU, it also shows the opportunity of adding a company specialized in waste collection to such project, even if Suez is not a big player on the battery market;
- cooperation between companies established in Europe such as SNAM with Peugeot PSA and Toyota (Lebedeva et al, 2017). Panasonic, Saft and Accurec also expressed the need for a better integration of EV manufacturers and recyclers (Mathieux *et al*, 2017);

- Furthermore, the construction of gigafactories in Europe will create a market for primary and secondary materials produced in Europe (recycled cobalt in Belgium and primary lithium in Portugal). As such, the planned gigafactories in Berlin (Tesla), Gdansk (Northvolt) or Hungary (Samsung) are further key components in the development of a European battery recycling industry.

If vertical integration as in China has little chance of being replicated in the EU, industrial integration and cooperation along the battery value chain supported by European institutions and member states shows great potential, even if questions arise about the time needed for such industrial developments. To the author's knowledge, no such evaluation study exists. Umicore, which already had industrial capacities, has planned to boost capactiy from 7,000 tonnes in 2018 to 100,000 tonnes by 2021; i.e. in approximately three years. However, the majority of the companies do not have the experience, the technology and the financing capacity of Umicore, so it is likely that these developments will take much longer to materialize to achieve the required scale.

Conclusion

The battery value chain is currently dominated by Asian countries, particularly China. With soaring demand driven by the development of the electric mobility across the world, global battery cell markets, and critical metals supplies will be under increasing strain. For the EU, which has little domestic supply of raw materials and is aiming for carbon neutrality by 2050, recycling will become a primary option in order to reduce external dependence and minimize its environmental impact. However, this process is not as simple as it may seem, and comes with a number of challenges.

While recycling consumes less energy than primary production,[9] it has to compete with cheaper primary production, even if the impacts of the latter such as pollution, emissions or end-of-life mining site management are externalities not yet taken into account. The economic consequences of environmental damages and supply insecurities are not calculated. Nor is the environmental impact of batteries over their whole life cycle, including manufacturing, accounted for. Yet if their production and the sourcing of refined metals is cheaper in China, it is only because of the cheaper labour costs, cheaper energy sources and lower environmental standards. Indeed, Chinese energy consumption relies primarily on coal (58%; BP, 2019), which is the most polluting energy source. As a result, the carbon footprint of the battery manufacturing industry in China in most cases is much higher than in the EU.

Recycling therefore needs new business and economic models. Solutions such as leasing coupled with eco-design or manufacturing standardization should be developed in conjunction with new economic models, favoring recycling and closed-loop organization, while also taking into account the real impacts of batteries and the real impact of the metals used in primary production. The EU has many advantages, including the quality of its infrastructures (carbon-free energy, transport, technology, etc.) and its education systems. The political environment is stable, which is important for investors. Furthermore, Europe's underground resources are not yet well-known and could allow the development of potential responsible mining activities. However, the EU has to implement more

9. In the case of aluminum, copper and iron, recycling even allows respectively 95%, 85% and 74% of the energy used to produce the same quantity of material from extraction to be saved (Cui and Forssberg, 2003). A closed-loop process for batteries would cut 51% of the environmental impact of their manufacturing process (Dewulf et al, 2010).

ambitious and responsible legislation, which takes the carbon footprint of the life-cycle and recycling processes into consideration, while also promoting second-hand, reuse and local distribution networks. The EU should also encourage university research to develop new models for measuring the environmental impact of products, within multidisciplinary programs.

If the EBA initiative rightly started with a focus on battery manufacturing in the EU, encouraging the development of a robust EU recycling industry will be equally important and requires efforts to modernize the legislation, improve technologies but, most importantly, to set up new industrial models. However, it also shows that recycling is not an end in itself and needs to be integrated into a value chain, and more generally into an industrial ecosystem. The change of the energy system brought about by the increasing use of batteries should be preceded by systemic thinking about its implications. If R&D initiatives for the battery value chain are necessary, they should also affect research on life cycle analysis (LCA) and material flow analysis (MFA), both methodologies allowing a better measurement of the environmental impacts of batteries, and of the flows of raw materials contained in end-of-life products.

Implementing such a strategy should help the EU to address some of the important issues it is facing nowadays, such as responsible sourcing, environmental pressure or future supply uncertainties. A coherent industrial policy should enable the EU to achieve some industrial and technological autonomy both for battery production as well as for raw material sourcing. Given the growing needs for battery metals, such a strategy could also diminish the tensions on mineral markets.

However, even if the recycling market will only become mature by 2025-2030, when EVs will massively enter the flows of collected waste, investment decisions for processes and infrastructures have to be taken now. This requires companies, which are generally focused on the short to medium-term, to make challenging decisions. The investments required are ofthen equivalent to several times companies' turnover, and neither their profitability nor their legal framework are stable. That is why Member States, by way of the EU, must re-take the helm of an industrial policy and provide the financial and political means to develop such an industry. At the EU level, an earlier revision of the EU battery directive could help spur these developments. It should indeed be recalled that today's high technology industries were created and encouraged by state-driven initiatives.

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