End-of-Life Scenario Analysis for Lithium-Ion Batteries from Passenger Car Electric Vehicles in the EU

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ABSTRACT

Lithium-ion batteries are the predominant technology for energy storage in electric vehicles. The rapid increase of electric vehicle sales that is seen today will lead to large volumes of batteries being retired in the years and decades to come. When batteries are too weak to satisfactory work in vehicles, they might still hold sufficient energy to work in a second life application. Finally, the recycling process can recover the critical materials inside the batteries.

A scenario analysis was developed for the years 2020 to 2030 to analyze the material flows from passenger car electric vehicle batteries in the EU and its implications on the economic, environmental, and political dimension.

The results suggest strong environmental and economic benefits of a circular battery value chain. By 2030, the economic value of materials inside retired passenger car electric vehicle batteries could surpass 1 billion Euro each year and the recovered metals could cover around 10% of the material demand for new batteries in Europe. Batteries available for second life could sum up to 30 GWh per year in 2030, but safety concerns and a lack of regulation are still hampering wide-scale adoption. Stronger legislative guidance is needed to achieve a circular battery value chain in the EU.

KEYWORDS

Material flow analysis, recycling, repurposing, second life

INTRODUCTION

Lithium-ion batteries (LIBs) are the state-of-the-art of high performing and reliable batteries, and the dominant energy storage system for electric vehicles (EVs). As such, they are one of the key components for the decarbonization of road transport but are not free from concern.

LIBs require the use of critical raw materials (cobalt, graphite, lithium) with volatile prices and high import dependencies for the EU. Furthermore, emissions related to raw material mining and battery production are high, and standard end-of-life (EOL) treatment of batteries fails to recover some of the key materials.

Despite those concerns, EV batteries can eliminate the large emissions associated to carbon fueled road transport. Coupled with a shift towards 100% renewable energy generation, EVs promise an almost carbon neutral transport sector. Furthermore, once EV batteries have reached their EOL, they might still hold sufficient energy to work several years as stationary storage systems, reducing the environmental impact of energy intensive battery production over the lifetime. Only after this second battery life, LIBs can enter a recycling process where the materials are recovered and supplied back to the battery manufacturing process, creating a circular material flow (Figure 1).

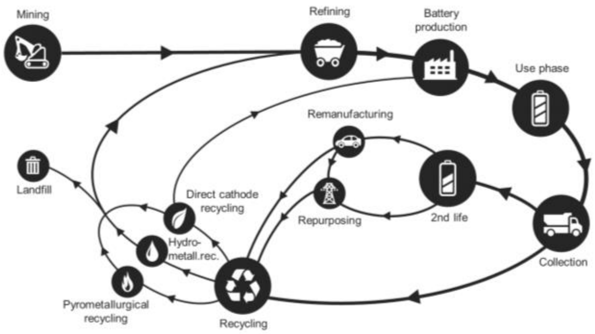


Figure 1 Life cycle of LIBs.

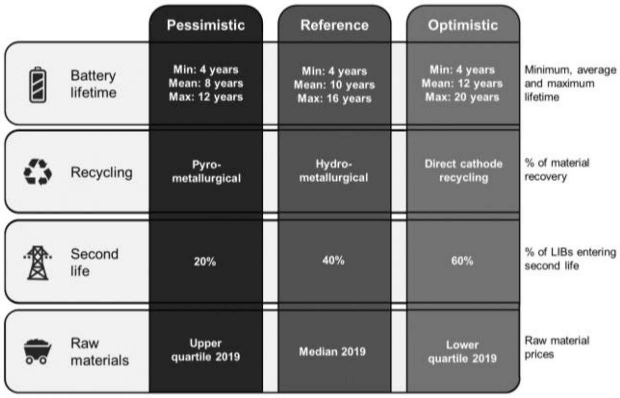
While the production of batteries is receiving much attention, the EOL sector for batteries in Europe attracts comparatively little attention, partly due to the fact that the numbers of automotive batteries reaching their EOL are still low. Recycling of LIBs is only performed in small quantities, and the reuse of batteries is still in the pilot stages. Furthermore, a clear regulatory framework for repurposing LIBs after first use is missing and concerns are rising about the safety of second life battery applications. While many questions remain unanswered, both recycling and reuse could be promising approaches to reduce costs and environmental impacts associated with LIBs.

This thesis presents a material flow scenario analysis for EOL LIBs in the EU from 2020 to 2030, and an evaluation of the economic, environmental, and political implications.

METHODOLOGY OF SCENARIO MODELLING

Scenarios are part of future and foresight science and can be described as “coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action” (van Notten 2005). Instead of claiming to predict how the future will turn out, scenarios are used to create alternative versions of the future and thus enable discussions in complex environments and help to deal with decision making under uncertainty. By creating multiple versions of the future, scenarios can broaden the view and reduce mental limitations (Schwartz 2005).

The goal of the scenario analysis in this work is to create plausible scenarios for the BEV and PHEV passenger car market in the EU and assess its implications on import dependency, environmental impact, and economics for the years 2020 to 2030. Four scenario dimensions were chosen that show great uncertainty but are expected to impact the future of the LIB industry strongly: Battery lifetime, recycling efficiencies, raw material prices and percentage of batteries entering a second life. For each dimension three distinct scenarios were set (see Figure 2), while other factors were set constant. In addition to the four scenarios, a sensitivity analysis was carried out to vary the number of BEV and PHEV sales and evaluate how strong the overall results are influenced by this factor.



	Pessimistic	Reference	Optimistic	
Battery lifetime	Min: 4 years Mean: 8 years Max: 12 years	Min: 4 years Mean: 10 years Max: 16 years	Min: 4 years Mean: 12 years Max: 20 years	Minimum, average and maximum lifetime
Recycling	Pyro-metallurgical	Hydro-metallurgical	Direct cathode recycling	% of material recovery
Second life	20%	40%	60%	% of LIBs entering second life
Raw materials	Upper quartile 2019	Median 2019	Lower quartile 2019	Raw material prices

Figure 2 Dimension and scenarios of the analysis.

The scenario analysis was implemented using Microsoft Excel spreadsheets and a Visual Basic for Application (VBA) script to cope with the high number of scenario combinations. The different scenario dimensions are decoupled from one another which increases the number of possible combinations to the power of three for each added scenario dimension.

The logic of the analysis is visualized in Figure 3.

The initial step of the analysis is the calculation of the kWh of BEV and PHEV batteries that enter the European market. Three inputs are required: Car sales, average battery size, and shares for different LIB chemistries. Historic data on sales, average battery sizes and shares of LIB chemistries was extracted from a market analysis of (Takeshita et al. 2019), which provided detailed information about the specifications of all the BEV and PHEV models and the corresponding sales numbers. Furthermore, the dataset included sales projections for the years 2020 to 2023, which were used as a reference to create an extrapolation for the years 2020 to 2030. Sales of BEVs and PHEVs together with the average battery sizes provide the kWh of batteries entering the market. The share of different battery chemistries is later used to quantify the material amounts inside the batteries. Based on the number of batteries entering the market, the EOL battery flows can be calculated by using three different functions as the lifetime scenarios. Once the EOL battery flows are calculated with their corresponding material quantities (based on materials per battery chemistry), they are combined with the material price (three scenarios). Calculations are then performed to quantify the impacts of different recycling and reuse scenarios on the economic, environmental, and political dimension. Afterwards, a sensitivity analysis is used to vary the number of EV sales (25% increase and 25% decrease) and measure its implications on the rest of the analysis, since EV uptake is a factor of great uncertainty but assumed to have a large leverage on the overall results. The following paragraphs give further information on the methodological approach for each input variable.

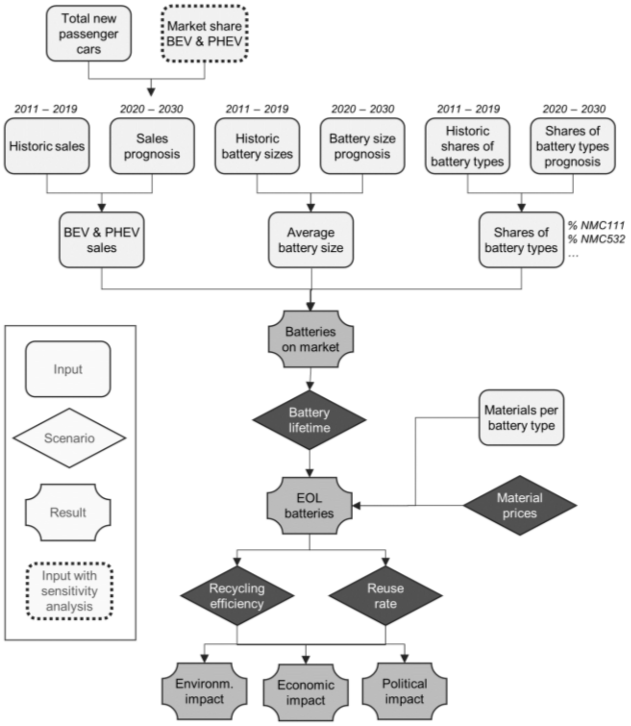


Figure 3 Schematic representation of the underlying logic.

BEV and PHEV sales

While the sales figures for 2011 to 2019 are based on historic numbers, the number of BEVs and PHEVs for the years 2020 to 2030 is calculated by using the total number of passenger car registrations in the EU and the expected share of BEVs and PHEVs out of newly registered vehicles.

In 2019, the European Parliament and the Council defined (in EU regulation 2019/631) CO_2 emission targets with an average of 95 g CO_2/km for newly registered passenger cars of each automaker (the regulation applies since January 1st, 2020). Furthermore, the regulation states that in 2025, 15%

of all passenger car sales should be zero- and low- emission vehicles[1] (ZLEV), and 35% in 2030.

In 2019, the market share of BEVs in new passenger car registrations in the EU was estimated by the European Alternative Fuels Observatory (EAFO) at 2,1%, and for PHEVs at 1,2% (EAFO 2020).

When estimating that ZLEVs will comprise all BEVs as well as those PHEVs with CO_2 emissions lower than 50 g/km. the growth rate of market penetration can be defined based on historic data.

The EU targets are assumed to be met, and the 2025 target (15% ZLEVs) assumed to be comprised of 11% BEV and 4% PHEV, and the 2030 target (35% ZLEVs) of 25% BEV and 10% PHEV.

To calculate the number of vehicle registrations for the years 2020 to 2030, the total number of car registrations must be known. The passenger car sales in the EU are approximated at 15 million each year and assumed to remain constant over the scenario period from 2020 to 2030. This corresponds to sales figures seen in recent years (ICCT 2019; ACEA 2020). The International Council on Clean Transportation (ICCT) reported passenger car registrations of 14,6 million in 2016, 15,2 million in 2017 and 15,1 million in 2018 (ICCT 2019).

Limitations:

- There are PHEVs which emit more than the threshold of 50 g CO_2/km and therefore are not counted as ZLEVs by the EU. Nevertheless, as a simplification for the analysis, all PHEV models are counted to contribute to fulfill the EU target. This is deemed acceptable since average battery size of PHEVs is increasing and thus PHEV emissions are expected to decrease further, and most PHEVs will fall under the category of ZLEVs.
- Only BEVs and PHEVs are counted as ZLEVs, while other vehicle types such as hydrogen powered fuel cell cars are neglected. To date, the share of such vehicles is negligible, but this could change in the future.
- The fixed number of 15 million newly registered vehicles in the EU each year is based on current sales figures. Future changes to this number are hard to predict and therefore a constant number is used for the analysis. Market effects due to the Corona pandemic are excluded.

Average battery size

The average battery size of BEVs and PHEVs entering the market was calculated based on historic data on BEV and PHEV models and sales from 2011 to 2019 and prognosis of sales for the years 2020 to 2023 (Takeshita et al. 2019). To calculate the historic numbers, the given sales numbers S for each EV model (total number of 333 BEV models and 246 PHEV models) in a certain year were multiplied with the battery size B of that EV model. The sum for all models was then divided by the total number of sales for the given year. Thus, the average battery size B_{av} in each year could be determined.

$$B_{av,BEV,2011} = \frac{\sum_{i=1}^{333} S_{i,2011} * B_i}{\sum_{i=1}^{333} S_{i,2011}}$$

The same approach was applied to calculate the average battery size of PHEVs.

Values from 2023 to 2030 were linearly approximated, assuming that average battery sizes will keep growing, corresponding to a customer demand for longer range EVs.

Limitations

- The calculation of average battery size is based on worldwide BEV and PHEV sales. The assumption is made that the average battery sales of EVs in the EU resembles that of worldwide EV sales.
- The prognosis of future battery sizes is done by linear approximation. Technological breakthroughs could nevertheless accelerate the development.

Shares of battery types

To estimate the amount of materials inside the vehicles, it must be known how many vehicles of each LIB cathode type entered the market. To estimate this number, an analysis based on historic EV data from (Takeshita et al. 2019) was carried out to estimate the shares of both BEV and PHEV models. Cathodes made of $LiFePO_4$ (LFP) and $LiMn_2O_4$ (LMO) batteries were excluded since they represent a marginal share in the dataset of passenger car BEV and PHEV sales. Thus, the focus is on LIBs with cathodes made of $LiNiCoAlO_2$ (NCA) as used by Tesla and LiNiMnCo (NMC) with varying weight shares as used by most other OEMs.

For a given year, the market share for each cathode type was calculated. This was done by multiplying the sale numbers of EV models with for example NMC111 cathode batteries (equal share of nickel, manganese, and cobalt in the cathode) S_{NMC111} with the battery size B (in kWh) of the corresponding model. The results were then divided by the sales numbers of all EV models S_{all}[2] multiplied with their corresponding battery sizes. The market share is thus representing the share that one battery chemistry has of the total battery capacity entering the market in a given year.

$$\begin{aligned} &Market\ share\ of\ NMC111\ cathodes_{BEV,2011} \\ &\quad = \frac{\sum_{i=1}^{333} S_{i,NMC111,2011} * B_i}{\sum_{i=1}^{333} S_{i,all,2011} * B_i} \end{aligned}$$

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[1] "Zero and low-emission vehicle' is defined as a passenger car or a light commercial vehicle with tailpipe emissions from zero up to 50 g CO_2/km, as determined in accordance with Regulation (EU) 2017/1151.

[2] S_{all} includes battery types with the cathode composition NMC111, NMC532, NMC622, NMC811, and NCA.

The future development of shares of battery chemistries was based on announced new EV models by the OEMs and sale projections until 2023 (Takeshita et al. 2019). Those values were extrapolated, while considering the trend of battery producers towards higher nickel contents in the cathode. Thus, the share of NMC811 is assumed to continue to grow strongly from 2023 onwards, reaching a market share of 80% in 2030. The higher cobalt chemistries NMC111 and NMC532 are assumed to fade out in 2024 and 2025 respectively, while LIBs with NMC622 cathode are assumed to still hold a 10% market share in 2030. NCA batteries (predominantly used in Tesla vehicles) are assumed to lose their currently high market share since other automotive companies increase their share of the EV market.

Limitations:

- Changes of materials among the LIB chemistry types are assumed to be only in the cathode materials. This is deemed acceptable since the cathodes contain the materials that are most relevant for recyclers.
- Changes in the weight composition of NCA batteries over time (also historically) are not considered due to the lack of data.
- The development of new, more efficient, safer, or cheaper types of batteries could diminish the dominant position of LIBs as EV batteries. Such developments will impact the entire value chain, especially the raw material demand and the profitability of recycling. Due to uncertainty about the direction of such technological changes they are not considered in the scenarios.

Battery lifetime scenarios

LIBs in EVs need to meet minimum performance standards. Over the years of usage, battery capacity fades due to cell degradation. At some point, customer demand for driving range can no longer be met. Most EV manufacturers give battery warranties of 8 years in which they guarantee at least 70% retained capacity. Similarly, the USABC defined the EOL of EV batteries when 80% of nominal battery capacity is reached (USABC 1996).

Battery degradation or aging has different causes such as growth of the solid electrolyte interface on the anode which decreases the accessible surface, electrolyte oxidation on the cathode with correlates to a loss of lithium, and other corrosion or decomposition effects (Jana et al. 2019) (Gennaro et al. 2020). The rate at which cells are aging is impacted by various factors such as number of cycles, speed of charging, load profiles and temperatures.

Recent experiments (Harlow et al. 2019) for a NMC532 pouch cell with an synthetic graphite anode showed only 4% capacity loss for 4.000 cycles at 20°C and with 100% depth-of-discharge (at C-rate[3] of 1), and a 12% capacity loss after 3.700 cycles for a constant temperature at 40°C. For the 40°C condition and a 300 km range EV this results in a total driving distance of 1.200.000 km which equals several decades of EV use. While such laboratory tests cannot represent reality, they nevertheless suggest a much longer lifetime than the manufacturer warranty period. In 2020 the JRC published a scenario analysis of capacity fade modelling for different driving ranges and recharge strategies (Gennaro et al. 2020). For NMC pouch cell LIBs with low power charging and long charging time (as seen when vehicles are charged overnight at home or during work hours at the office), the analysis results in a lifetime of 4,6 to 9,7 years dependent on the monthly driving range.

Based on the aforementioned numbers, three different battery lifetime functions were defined.

The average lifetime until EOL is reached various between 8 years (short lifetime scenario), 10 years (reference scenario), and 12 years (long lifetime scenario). Furthermore, for each scenario it is assumed that 1% of batteries will reach their EOL already after 4 years of usage, representing load profiles with exceptionally high yearly driving distances. The maximum lifetime, which 1% of batteries reach, ranges from 12 (short lifetime scenario) to 16 (base case scenario) and 20 years of usage (long lifetime scenario).

Those 3 scenarios were translated into probability distributions using a Gauss function that meets the average lifetime requirement and intercepts at 4 years. For the scenario analysis calculations, the Gauss functions were converted into discrete probability distributions where each year is represented by one discrete value and the sum of values equals 100%.

After the first battery life ends, all batteries are assumed to stay in Europe, without any export of EOL vehicles outside of Europe. However, it should be noted that the European Commission allows the export of EOL vehicles and waste outside of the EU under certain obligations such as that EOL vehicles which are exported to third countries still comply with the EU recycling and recovery regulation (European Commission 2005). Due to lack of data on the export of EOL vehicles this model assumes that all vehicles and batteries are treated within the EU.

Limitation:

- Due to the short period that EVs started entering the market in higher numbers, there is a lack of real-life data on battery lifetime. Accuracy of the battery lifetime scenarios can be improved once long-term studies have been conducted.
- Export of EOL vehicles or batteries outside the EU is neglected.

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[3] C-rate measures the rate of charge/discharge relative to the batteries nominal capacity. A C-rate of 1 will charge/discharge the battery in 1 hour, a C-rate of ½ in 2 hours.

- When calculating the number of EOL batteries, a collection rate of 100% is assumed. The EU set out the target of 45% collection rate by 2016 in the Battery Directive (European Commission 2006). However, EV batteries are assumed to show much higher collection rate compared to household batteries, due to their size and fixed position inside the body of the car, making it likely that they remain inside EOL vehicles where they can be recovered by the treatment facilities.

Materials per battery type

To calculate the amount of materials that can potentially be recovered from EOL batteries, the weight shares of each different LIB chemistry must be known.

The material composition for each battery type was derived from (Takeshita et al. 2018, 2019). For the different NMC cathode types, it was assumed that only the cathode composition changes while all other battery materials remain identical. This was deemed acceptable since the detailed analysis on economics and environmental impact was carried out with focus on 8 key materials, who show the greatest relevance to the recycling process (aluminium, graphite, lithium, nickel, copper, steel, cobalt, and manganese). The amount of those materials in LIBs is mainly impacted by the composition of the electrodes (except steel and part of aluminium and copper).

To calculate the materials inside EOL batteries, four factors play together: the battery lifetime distribution, the amount of batteries entering the market, the share of the different cathode chemistries for the given year and finally the material amounts within each LIB type.

The calculation is exemplary carried out for the year 2023, to estimate cobalt amounts within BEV NMC111 batteries that reach their EOL in 2023. The calculation is carried out only for the short battery lifetime scenario (average of 8 years, minimum of 4 years, maximum of 12 years).

When calculating the amount of materials reaching EOL in 2023, batteries that entered the market between 2011 and 2019 must be considered. For each of those 9 years, the GWh of batteries entering the market $B_{tot,BEV,2011-2019}$ is multiplied with the share of NMC111 batteries for the same year $\%NMC111_{BEV,2011-2019}$, thus providing the GWh of NMC111 batteries that entered the market in a given year. The result is multiplied with the lifetime function (converted to discrete values).

For the short lifetime scenario, 1% of batteries will enter EOL after 4 years of usage, 5% after 5 years, 12% after 6 years, and so forth until the maximum lifetime of 12 years is reached, which 1% of batteries reach. Thus, when calculating the EOL batteries in 2023, 1% of the NMC111 batteries that entered the market in 2019 are counted, 5% of those in 2018, and so on. The total sum for the 9 years is finally multiplied with the weight of cobalt inside NMC111 batteries.

To calculate the total amount of cobalt in EOL batteries for a given year, the same calculation is carried out for all the different battery chemistries and for PHEVs and everything is added up.

Limitations:

- Only the cathode compositions are changed for the different material compositions, while module and pack materials remain identical.
- All NMC cells are assumed to have a pouch cell format, and all NCA cells a cylindrical casing. Both limitations have a minor impact on the results since the focus of the analysis is primarily on the materials within the electrodes of the battery cells.

Raw material price scenarios

The prices of the LIB raw materials show great fluctuations over time and are influenced by many factors such as demand, technological progress of batteries and extraction methods, or political situations in the countries where the mining takes place. Therefore, it is difficult to predict a reasonable future scenario. Instead of developing an economic model to predict future price development, the range of historic price variations was analyzed.

The monthly prices were collected from DERA and originate from European and international metal markets such as LME, SMM and Metal Bulletin. Prices were converted from US dollars and Chinese renminbi to Euro using historic exchange rates derived from (TransferMate 2020).

The 12 prices for each month of the year 2019 were then used to calculate the medium value, as well as the high and low quartile. The period for the historic values was set to 2019, since it was the only full year for which all data points were available.

Limitations:

- The assumption was made that the price of recycled materials is identical to that of new materials. In reality, dependent on the quality of the recycled material, prices between virgin and secondary materials will vary.
- No projection of future price development is used. Instead, historic price fluctuations from the year 2019 are assumed to give indications about future price ranges. Future prices can nevertheless deviate strongly from past values, due to changes in overall market demand, new suppliers or extraction technologies, or unforeseeable events such as economic crises.
- The market prices are defined for the commodities that are traded on international metal market and were selected to represent the raw materials within LIBs adequately. However, accurate data about the quality requirements for battery materials by the producers was missing. If higher grade materials are required, prices could rise.

Recycling scenarios

European LIB recyclers must meet the EU recycling efficiency target of 50% but they are free in choosing the recycling technology to achieve the target. 3 different recovery rates for individual materials are used as the recycling scenarios. They are based on approximations for 3 different LIB recycling technologies: pyrometallurgy, hydrometallurgy and direct cathode recycling.

The recovery rates are derived from the closed-loop battery recycling cost and environmental impacts model (EverBatt) developed by Argonne (Dai et al. 2019). The recycling efficiencies are conservative estimations of industrial pyrometallurgical and hydrometallurgical processes. Pyrometallurgy is assumed to lose aluminium, graphite, lithium and manganese to the slag, while hydrometallurgy is able to recover those materials with recovery rates ranging from 90% to 98%. Direct cathode recycling is estimated to have the same recovery rates as hydrometallurgy but will regenerate the cathode active materials together. However, it should be noted that this approach is still in the research stage.

Limitations:

- The focus lays only on the recovery rates of metals and graphite since they are deemed to be politically most important and most relevant for the economics of recycling, due to high weight shares and high market prices.
- No distinction was made between different process qualities within each recycling technology. The recovery rates are estimations of average process qualities.
- The GREET model assesses the recycling at cell level, since there is a lack of data on recycling of cooling systems or BMS. This has a small impact on the scenario analysis since the materials which are analyzed are predominantly found in the battery cell (apart from steel and partly aluminium and copper).

Second life scenarios

The second battery life market is still in its infancy, making predictions about its uptake difficult. Critical issues such as safety and regulations remain under investigation. Nevertheless, it is of interest to analyze the implications that a prolonged lifetime could have on economies of scale in recycling and the dependency on import of materials.

To estimate the potential benefits of large scale second battery life, three different rates of reuse are set: 20%, 40% and 60%. The rates of reuse are hereby defined as the percentage of batteries (kWh) that enters a second life. The batteries are assumed to function as a stationary energy storage system with moderate utilization such as a system providing frequency regulation to the grid or buffering intermittent renewable energy.

While usage of the batteries in EVs is highly dependent on individual driving behavior (covered mileage, charging patterns, etc.), stationary storage systems are expected to have a more stable load profile and benefit from regular maintenance. Therefore, in contrast to the distribution function implemented for LIB first life in EVs, the second life application is assumed to have a fixed lifetime of 10 years, as suggested by (Neubauer et al. 2015).

The remaining capacity at the start of the second battery life is assumed to be at 80% if its original value.

Limitations:

- The fixed lifetime of 10 years is an approximation. Second lifetimes will vary dependent on the first life load profile, cycling behavior, and other factors such as temperature or maintenance.
- To date, no reliable data on the rate of LIBs that are eligible for second life exists, the three scenarios are therefore solely used to simulate the implications that different reuse rates can have while acknowledging that technical feasibility still has to be proven.
- The capacity fade during the first battery life will vary. Nevertheless, due to the lack of actual data on second life batteries, a fixed value of 80% is set.

RESULTS OF SCENARIO ANALYSIS

Battery demand and supply

With the average BEV battery capacity gradually growing from 61 kWh in 2020 to 74 kWh in 2030 and a PHEV capacity starting at 16 kWh in 2020 and increasing to 31 kWh in 2030, the required battery production capacity to meet the EU demand was calculated. The filled grey bar charts in Figure 4 show the estimated battery production demand for BEVs and PHEVs in the EU, while the striped bar charts show the announced buildup of domestic LIB production facilities in EU countries. The line chart furthermore shows the development of EV market shares, reaching a summed share of 35% BEVs and PHEVs by 2030.

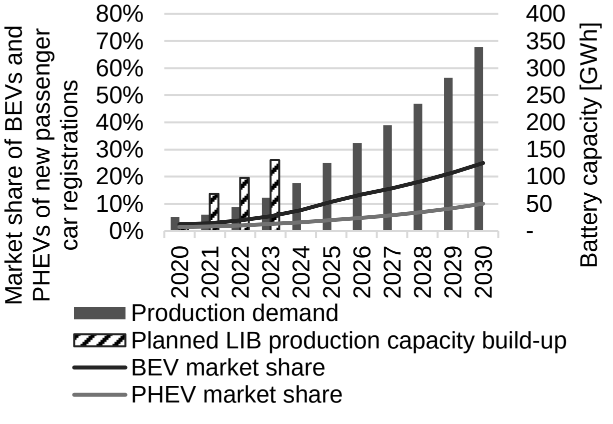

Figure 4 LIB market demand and supply. Left axis: BEV & PHEV market shares of newly registered passenger cars in EU; Right axis: LIB capacity (in GWh).

The passenger car LIB demand in the EU is expected to increase drastically. While in 2020 values were calculated to reach approximately 25 GWh (BEV and PHEV), values increase fivefold in just 5 years to 125 GWh. Numbers continue to grow strongly and more than double in the next 5 years and reach 339 GWh in 2030.

The increase in battery demand suggested by the results corresponds to high investments into European LIB production facilities. While Europe's contribution to the 150 GWh of global LIB cell manufacturing capacity (2018) is negligible today (Huisman et al. 2020), production facilities are ramping up quickly. Northvolt is building up a 32 GWh plant in Sweden, LG Chem is building their largest global LIB production facility in Poland with a capacity of 65 GWh and in Germany several LIB production plants are currently under construction. CATL is constructing a 24 GWh plant in Erfurt, Farasis builds a 10 GWh facility in Bitterfeld-Wolfen, and VW created a joint venture with Northvolt to create a 16 GWh LIB plant in. Only with this non-exhaustive list of upcoming LIB production, production will grow by 130 GWh until 2023. The results of the analysis indicate that the EU will be able to meet the demand for BEV and PHEV batteries (for passenger cars) with domestic LIB production in the upcoming years (filled vs. striped bar chart in Figure 4). It remains to be seen how the economic impacts of the Corona crisis in 2020 will hamper the construction of the production facilities and the battery supply chain as a whole.

End-of-life batteries

After the number of vehicles entering the market was calculated, the battery lifespan scenarios can be used to estimate the number of vehicles and the respective kWh of LIBs that reach their EOFL.

Calculations were performed for the 3 different LIB lifetime scenarios. The different scenarios result in large variations in the numbers of batteries reaching EOL in the upcoming years. In 2020, numbers reach from 0,2 GWh for the long lifetime scenario to 0,7 GWh for the short lifetime scenario. In 2030, numbers reach a minimum of 19,1 GWh and a maximum of 50,9 GWh.

The results show an exponential increase in EOL battery capacity in the EU, whereas large differences exist between the scenarios. In 2030, the difference between the 8 years and the 12 years average battery lifetime scenario results in a gap of 30 GWh (which equals 500.000 BEVs with a 60 kWh battery).

Even though the different lifetimes are merely delaying the numbers of EOL batteries by a few years, the implications on business decisions and development of the recycling industry can be vast. For example, the recycling facilities in Europe must be able to handle the volumes of EOL batteries and ramping up of recycling capacities can be a time-consuming process. Similarly, domestic battery producers require a stable supply of raw materials, which can be guaranteed by long-term contracts with virgin material suppliers. If battery producers want to integrate the more sustainable option of using recycled materials, the deviations of EOL batteries shown in the scenarios make it difficult to predict the amounts of recycled materials that will be available. The more sustainable option of using recycled materials can thus become less appealing if the supply risks are high due to unknown streams of EOL batteries.

Regardless of the uncertainty, it can be assumed that quantities of batteries from electric vehicles entering the waste streams will increase drastically in the upcoming years, which requires the ramping up of an EOL industry that can handle the EOL battery volumes.

For the three lifetime scenarios, Figure 5 shows battery demand versus the amount of battery materials entering their EOL for cobalt and nickel. The material demand for battery production is plotted against the theoretical maximum supply of raw materials from EOL batteries.

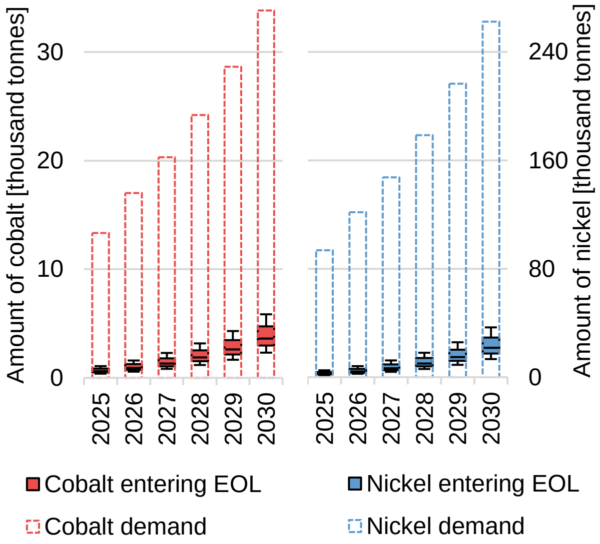

Figure 5 Material demand and EOL materials for cobalt and nickel from 2025 to 2030.

The trend in LIB cell chemistries towards lower cobalt contents reduces the amount of cobalt that is required for newly produced batteries. At the same time, the nickel share inside newly produced LIBs is rising. Thus, cobalt from EOL batteries could theoretically cover around 10,7% of material demand in 2030, while for nickel it is only 8,2% in 2030.

In general, the overall impact of the chemistry changes is weakened by the strong increase of BEV and PHEV sales, which reduces the share of EOL materials compared to the strongly growing material demand.

Recycling

The tons of raw materials eligible for recycling derives from the number of EOL batteries and their respective capacity and chemistry. While number of BEVs and PHEVs on the roads and size of batteries are constantly increasing, battery chemistries are moving towards lower cobalt contents to avoid the critical raw material.

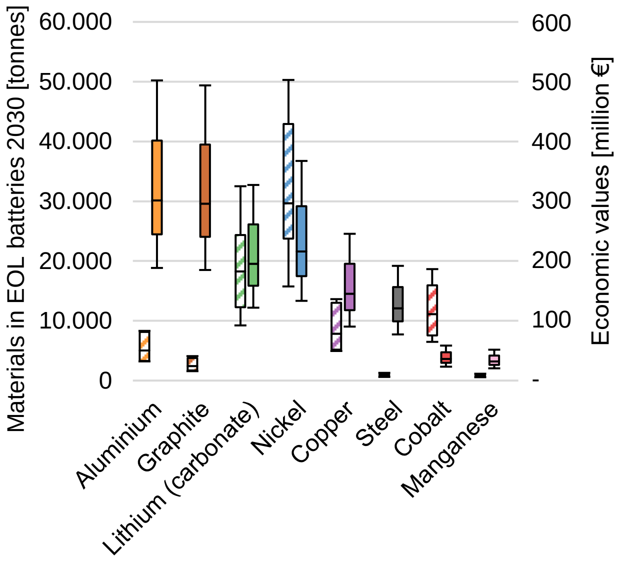

Figure 6 Materials inside LIBs that reach their EOL in 2030 (full bars), and the corresponding economic value (striped bars).

Figure 6 presents as the results for 9 scenarios (3 lifetime, 3 raw material price scenarios) the amount of materials in batteries that reach their EOL in 2030. Furthermore, on the right y-axis, the corresponding economic value of the EOL battery materials is plotted as striped boxplot diagrams. The graph presents the potential ideal economic value of material inside EOL LIBs for the different scenarios, when assuming a collection rate of 100% and complete material recovery in the recycling processes. The defined scenarios result in materials worth several hundred million Euros being eligible for recycling every year. In 2030, quantities of aluminium and graphite are highest among the materials, nevertheless their economic impact is comparably low due to the low material prices. Nickel and lithium show the highest economic importance, followed by copper and cobalt. Steel and manganese account for the smallest economic value within the materials.

The graph furthermore shows the impact of chemistry changes towards lower cobalt contents. Even though cobalt is by far the highest priced material, the economic importance within the LIB materials is reducing over the years. Figure 7 furthermore emphasizes this finding by showing the development of economic value (mean value of the scenarios) over the years (2015 to 2030) on a logarithmic scale. The scenarios depict a development in which cobalt started off in 2015 with the highest economic impact within EOL LIB materials, but the value diminishes in importance over the years. Cobalt is passed in terms of economic importance by nickel in 2020 and by lithium in 2022.

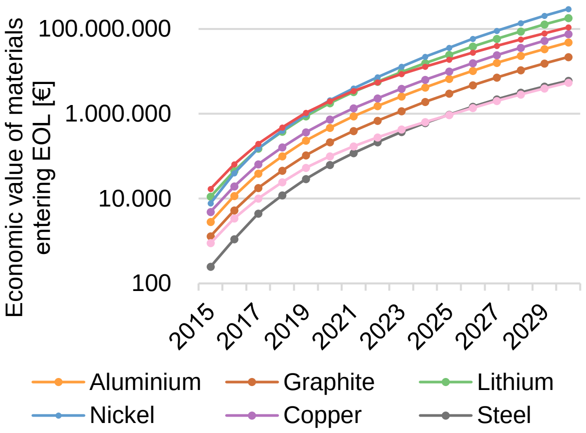

Figure 7 Economic value of materials in EOL batteries from 2015 to 2030.

Current recycling processes will not be able to make use of the full economic value present in EOL batteries due to losses during collection and an incomplete recovery rate. When considering that 100% of batteries are collected but all recycling processes will follow a pyrometallurgical route (without lithium recovery), the results of the scenarios anticipate macroeconomic losses that could rise above 100 million Euros each year by the end of the 2020s (see Figure 8, calculated with mean value of the scenario results).

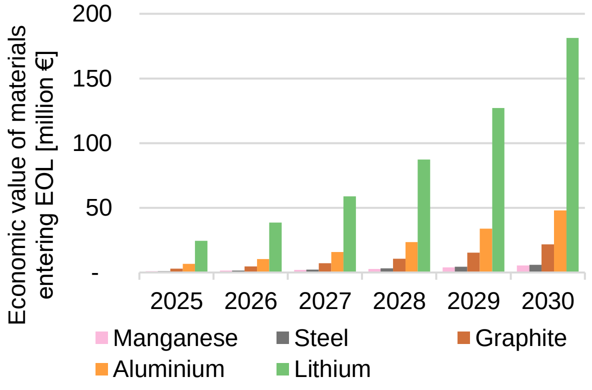

Figure 8 Economic value of lithium, aluminium, graphite, steel and manganese in EOL batteries from 2025 to 2030.

If the recycling furthermore fails to recover graphite, aluminium and manganese, many more million Euros are lost. However, lithium shows by far the highest economic impact of the materials that are potentially lost when using pyrometallurgy. These losses could reversely be counted as benefits of hydrometallurgical recycling processes and direct cathode recycling when subtracting the losses during those processes. With a recovery rate of 90% (lithium, aluminium, graphite, and steel) and 98% (manganese), the potential economic value of these 5 materials accounts to 2 million € in 2020, 33 million Euros in 2025, and 237 million € in 2030. It should however be noted that the recovery rates of pyrometallurgy are increasing and it might soon be economically feasible to recover lithium via hydrometallurgy from the slag of the pyrometallurgical recycling route.

For the approach of direct cathode recycling, it remains uncertain whether the technology can move out of the research stage. Recyclers must handle constantly changing cathode chemistries, and batteries that are retiring today are from the early EV generations with cathode chemistries such as NMC111 that are not produced anymore. As long as the technological development of cathodes continues, the approach of direct cathode recycling could remain in the concept stage.

The results of the scenario analysis emphasize the importance of the quality of the recycling process. On the macroeconomic level, the European market could waste thousands of tons of precious materials worth several hundred million Euros. Especially for materials with high EU import reliance, defined as the ratio of net import to apparent consumption, such as lithium (100%), manganese (90%) and natural graphite (98%) (Eynard et al. 2020a, 2020b), the political implications of low quality recycling processes are huge and will grow even more in the next decade.

These macroeconomic considerations are of no primary interest for the local recyclers, where complexity of the process and short-term profitability can be essential factors for making business decisions. To prepare the recycling industry for rising volumes of EOL batteries and secure the domestic supply of recycled raw materials, countermeasures must be taken from policy makers. The current EU recycling recovery rate of 50% is very low and does not specify which materials must be recycled.

Second life

When LIBs reach their EOL as EV batteries, they can still be suitable for usage in lower demand applications. However, the share of EOL batteries that will meet performance and safety requirements is difficult to predict to this day. To nevertheless assess the implications of hypothetical reuse scenarios, a recovery rate of 20%, 40% and 60% was defined.

Figure 9 shows the variations of GWh of batteries that would be eligible for second life for a total of 9 calculated scenarios (3 lifetime, 3 reuse scenarios) when assuming a 100% collection rate. The values rise to a maximum of 31 GWh of second life batteries in 2030 for the short lifetime (average of eight years) and 60% reuse scenario. Estimating an average capacity fade of 20% (80% remaining capacity) when batteries enter their EOL, this would still amount to 24,8 GWh of battery storage capacity.

The lowest scenario (long battery lifetime of 12 years average, and low reuse rate of 20%) sums up to 3,8 GWh in 2030.

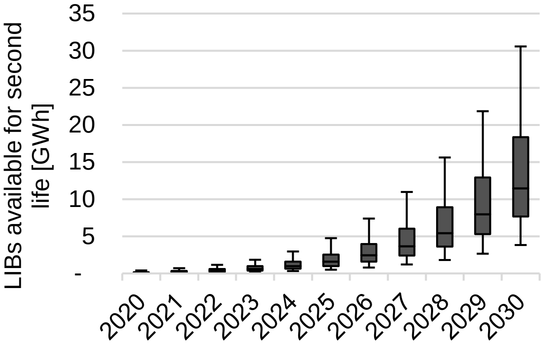

Figure 9 GWh of LIBs eligible for second life from 2020 to 2030.

While the scenarios paint a future in which second life battery can accelerate the energy transition by offering large scale, cheap energy storage, the technical feasibility remains uncertain due to the concerns about safety and lack of knowledge and aging behavior. Furthermore, second life batteries must compete with new batteries. Prices of batteries have been steadily reducing over the years while at the same time battery capacities go up. Why invest in second life batteries and risk system failure and high costs for maintenance if new and reliable batteries are cost competitive? Furthermore, the question of liability for second life products is not sufficiently answered.

If batteries are used in a second life for several years, the recovery of the materials via recycling is delayed. While recycling facilities today still wait for economies of scale to kick in and lower the recycling cost, high reuse rates work against this development by delaying the availability of EOL batteries.

Sensitivity to EV uptake

Two additional scenarios were defined for the EV uptake, with a 25% increase and 25% reduction of the share of EVs out of newly registered passenger cars in the EU.

The results show a direct correlation between EV uptake and battery demand which increases the range of scenario results drastically. However, when analyzing the EOL sector, a change in the EV uptake is only marginally impacting the number of EOL batteries in the near-term future. The results indicate that different approximations of the future BEV and PHEV development are not that important for calculating the EOL batteries for the near-term future (<10 years). Due to the long lifetime of LIBs, the historic sales figures are most essential for the approximation of the EOL batteries that will retire in the following years. Thus, the objective should be to accurately track the number of EVs that enter the roads every year. Furthermore, a better understanding of collection rates for EV EOL batteries (with a distinction between different types of batteries) is needed and better data on the export of old vehicles outside of Europe.

CONCLUSION

A scenario analysis was developed in which the volumes of EOL batteries in the EU was calculated and the economic value, environmental impact, and political importance of the materials within those batteries analyzed. The results indicated that the buildup of LIB production facilities in the EU will be sufficient to meet the domestic LIB demand for passenger cars in the upcoming years. With the strong increase in BEVs and PHEVs on the road, the number of EOL batteries is expected to increase strongly. The materials inside those EOL batteries present an immense economic factor and could cover up to 10% of production demand by 2030 as suggested by the scenario results. Especially for critical materials such as cobalt, the recovery from EOL batteries could become an essential material input stream for the domestic battery manufacturing.

On the macroeconomic scale, recyclers should be encouraged to recover lithium, due to its high weight share and economic value, coupled with a high European import dependency. Economically speaking, due to the decreasing cobalt contents, lithium becomes the second most important material inside LIBs (after nickel) from 2022 onwards.

To improve the accuracy of macroeconomic analyses and predictions of EOL battery flows, a tracking system for number of batteries entering the market with their corresponding battery sizes would help to accurately predict the EOL battery volumes in the upcoming years.

The environmental, economic, and political implications of different EOL battery treatments are huge and further guidance from the EU is needed to promote a circular LIB ecosystem in Europe. It remains to be seen whether the revised EU Battery Directive that will be published in the upcoming months can live up to these expectations.

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