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

Robin Rainer Barkhausen

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Fernanda Maria Ramos da Cruz Margarido

Dr. Tim Hettesheimer

Examination Committee

Chairperson: Prof. Edgar Caetano Fernandes

Supervisor: Prof. Fernanda Maria Ramos da Cruz Margarido

Member of the Committee: Dr. Patrícia de Carvalho Baptista

November 2020

Acknowledgements

I would like to thank the Fraunhofer ISI for giving me the opportunity to write my master thesis in their remarkable institution. My gratitude goes especially to my supervisors Tim Hettesheimer and Antoine Durand who guided me throughout the project.

Furthermore, I am very grateful for the constant support and feedbacks of my supervisor at the Technical University of Lisbon, Professor Fernanda Maria Ramos da Cruz Margarido.

Resumo

O rápido aumento das vendas de veículos elétricos a que hoje se assiste, levará à existência de grandes volumes de baterias em fim de vida nas próximas décadas e anos. No entanto, quando as baterias já não possuem a energia suficiente para funcionarem satisfatoriamente em veículos, podem ainda manter a energia suficiente para funcionar numa aplicação de segunda vida.

Foi realizada uma revisão da literatura sobre as baterias de iões de lítio, durante as diferentes fases de vida, com enfoque nas perspetivas económica, ambiental e política. As matérias-primas existentes nas baterias de iões de lítio são avaliadas, os processos de fabrico analisados, as estruturas legislativas apresentadas e as duas alternativas de fim de vida, de reciclagem e reutilização estudadas. Com base no conhecimento acumulado, são desenvolvidos diferentes cenários para 2020 a 2030 de modo a analisar os fluxos de materiais das baterias de veículos elétricos de passageiros na EU, e suas implicações.

Os resultados sugerem fortes benefícios ambientais e económicos numa cadeia de valor circular das baterias. Em 2030, o valor económico dos materiais das baterias em fim de vida, de veículos elétricos de passageiros, poderá ultrapassar 1 bilião de euros por ano e os metais recuperados poderão cobrir cerca de 10% da procura de materiais para a produção de novas baterias na Europa. As baterias disponíveis para segunda vida podem atingir 30 GWh por ano em 2030, mas as preocupações com a segurança e a falta de regulamentação ainda impedem a sua adoção em larga escala.

Palavras-chave: Análise de fluxo de material, reciclagem, reaproveitamento, segunda vida, matérias-primas críticas

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 literature review on the lithium-ion battery along its life stages with a focus on the economic, environmental, and political perspective was carried out. Raw materials inside Lithium-ion batteries are assessed, the manufacturing processes analyzed, the legislative frameworks presented, and the two end of life alternatives recycling and reuse studied. Based on the gathered knowledge, different scenarios for 2020 to 2030 are developed to analyze the material flows from passenger car electric vehicle batteries in the EU and its implications.

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, critical raw materials

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Acronyms

AB	Acetylene black
BatPaC	Argonne Battery Performance and Cost Model
BEV	Battery electric vehicle
BMS	Battery management system
CB	Carbon black
CO_2	Carbon dioxide
CMC	Carboxymethyl cellulose
DMC	Dimethyl carbonate
DERA	German Mineral Resources Agency
DOD	Depth of discharge
DRC	Democratic Republic of Congo
EAFO	European alternative fuels observatory
EBA	European Battery Alliance
EC	Ethylene carbonate
EF	Environmental Footprint
EFTA	European Free Trade Association
EOFL	End-of-first-life
EOL	End-of-life
ESS	Energy storage system
EU	European Union
EV	Electric Vehicle
EverBatt	Argonne Closed-Loop Battery Recycling Cost and Environmental Impacts Model
EWEA	European Wind Energy Association
GHG	Greenhouse gas
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
HRC	Hot rolled coiled
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
JRC	Joint Research Institute
Kg	Kilogram
ktoe	Kilo tonnes of oil equivalent
LCOE	Levelized cost of electricity
LDCs	Least developed countries
Li^+	Li-ion
LIB	Lithium-ion battery
Li_2CO_3	Lithium carbonate

LiOH	Lithium hydroxide
$LiPF_6$	Lithium hexafluorophosphate
LME	London Metal Exchange
$LiMO_2$	Lithium metal oxide
NDC	Nationally determined contribution
NiCd	Nickel-cadmium
NiMH	Nickel metal hydride
NMP	N-methyl pyrrolidone
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
PE	Polyethylene
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in hybrid electric vehicle
ppm	Parts per million
PVDF	Polyvinylidenfluorid
SASLAB	Sustainability Assessment of Second Life Application of Automotive Batteries
SBR	Styrene-butadiene rubber
SIDS	Small island developing state
SLB	Second-life battery
SMM	Shanghai Metals Market
SOC	State of charge
SOH	State of health
TRL	Technology readiness level
V	Volt
V2G	Vehicle to grid
V2H	Vehicle to home
VBA	Visual Basic for Application
VC	Vinylene carbonate
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
ZLEV	Zero and low emission vehicle

1 Introduction

1.1 Context and Problematic

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, some with limited worldwide reserves and import dependencies for the EU. Furthermore, battery production is highly energy intensive, and the end-of-life (EOL) treatment of batteries fails to recover some of the key materials.

Despite those concerns, if batteries are used to power EVs they 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.

In December 2019, the European Union (EU) announced its goal to reach carbon neutrality by 2050 (European Commission 2019d). To achieve this ambitious target a large decarbonization process is needed. One of the critical sectors is transportation, a sector which is responsible for a quarter of the EU's GHG emissions (European Commission 2019d). Road transport alone covers 29% of the final EU energy consumption (see Figure 1.1.1) making a shift to less carbon intensive technologies in this field indispensable.

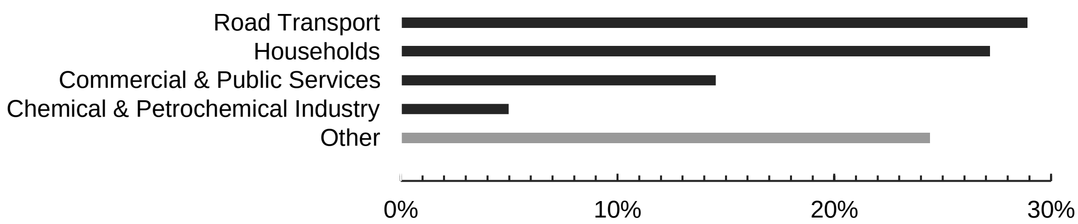

Figure 1.1.1 Largest contributors to final energy consumption in Europe (EU-28) in 2017 [1].
Numbers based on: (Eurostat 2019)

One way to achieve this goal is to promote renewable energy and couple it with the electrification of road transport. Automakers in the EU are forced to comply with tightening emission standards, with the target of 95 g CO_2/km for the average emissions of their passenger car fleet by 2021 as defined in regulation 2019/631 of the European Parliament and of the Council (European Parliament 2019), a value that most companies are currently failing (European Environment Agency 2020).

Therefore, all major automotive companies invest heavily into the electrification of their fleet, and governments incentivize final customers to buy EVs. In 2019, the pioneer country of promoting electric

[1] EU-28 total final energy consumption of 1.060.037 kilo tonnes of oil equivalent (ktoe) in 2017.

vehicles in Europe, Norway, was first surpassed by Germany in number of total EV registrations (Germany: 63.281, Norway: 60.316) (OFV 2020) (KBA 2020). Market shares of EVs are still low in most countries, but the trend towards electrification of road transport is clear and continued growth is projected. The European Alternative Fuels Observatory (EAFO) counts a European wide fleet size of 698.477 full electric passenger car vehicles, 3.207 electric buses, and 255 heavy-duty vehicles in 2020 (EAFO 2020b). Due to the small number of electric buses and heavy-duty vehicles on European roads to date, the focus of this study will solely be on passenger car electric vehicles.

In the EU a passenger car is defined as "a road motor vehicle, other than a moped or a motor cycle, intended for the carriage of passengers and designed to seat no more than nine persons (including the driver)" (Eurostat 2016).

Within passenger car EVs, both full battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), who combine a battery fueled electric engine with typically a classical combustion engine, will be assessed.

A critical component in EVs is the traction battery, where today most commonly LIBs are used, due to their supreme performance compared to other battery types. The costs of EVs are largely influenced by the price of the battery, which accounts for a major share of the total vehicle cost (54% cost increase of EV powertrains compared to conventional combustion engine powertrains) (Lutsey and Nicholas 2019).

Furthermore, the batteries are a potential cause for environmental problems and ethical concerns. EV batteries are associated with high GHG emissions, in part caused by the energy intensive battery manufacturing process if fossil based energy sources are used (Hall and Lutsey 2018). The manufacturing further requires the use of critical raw materials whose mining is concentrated in a limited number of regions like the lithium triangle[2] in South America, place of almost 60% of worldwide lithium resources (USGS 2020), and raises in part ethical concerns about working conditions like in the case of cobalt in the Democratic Republic of Congo (DRC), where 15-20% of extraction is done by artisanal mining (Banza Lubaba Nkulu et al. 2018).

To decrease import dependencies and increase the European share on the growing global battery market, the EU set out the goal to build up its own competitive manufacturing value chain for batteries. In 2017, the European Battery Alliance (EBA) was launched to promote industry collaboration, and as part of the Important Projects of Common European Interest (IPCEI) initiatives in the field of batteries receive financial support. The battery industry is furthermore guided by the construction of a legislative framework that covers the entire life cycle of batteries, as shown by the Study on the Ecodesign of Batteries[3] in 2019 and the current revision of the Battery Directive[4].

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 only few automotive batteries have

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[2] Lithium extraction site at the borders of Argentina, Bolivia and Chile. Estimated Lithium resources of total 80 million tons: Bolivia: 21 million tons, Argentina: 17 million tons, Chile: 9 million tons USGS 2020.
[3] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1.
[4] EU Directive 2006/66/EC.

entered their EOL. 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 applications. While many questions remain unanswered, both recycling and reuse could be promising approaches to reduce costs and environmental impacts associated with LIBs.

With the increasing numbers of EV sales, it is only a matter of time until large quantities of old batteries will need treatment, raising the question: What is the most economical and least carbon intensive EOL strategy for automotive LIBs?

1.2 Research Approach

On the background of the growing battery market and the upcoming need for adequate EOL battery treatment, the goal of the thesis is to analyze the corresponding market situation in the EU and perform a scenario analysis to identify advantages and disadvantages of different EOL strategies for different plausible scenarios. Available technologies and strategies for recycling and reuse of batteries will be assessed and evaluated from an economical, an ecological and a political standpoint.

In the course of the thesis six research question will be answered.

- RQ1 Which raw material inside a state-of-the-art LIB causes the highest GHG emissions?
- RQ2 What battery chemistry is most used in passenger car EVs today?
- RQ3 What recycling technologies for LIBs from EVs exist and what is their economic and environmental impact?
- RQ4 Which second life applications exist for LIBs from EVs, and what is their economic and environmental impact?
- RQ5 How much of raw material demand to produce passenger car EV batteries can be covered through recycled materials in the EU?
- RQ6 Which regulatory changes are needed to achieve a European LIB value chain optimized towards circularity?

As shown in Figure 1.2.1 the thesis is structured into 2 thematic blocks and 6 chapters.

Chapter 1 introduced the topic and presents the research approach.

Thereafter, Part A of the thesis describes the current state of the battery market, by presenting the state-of-the-art of LIB technology for electric vehicles and the end-of-first-life (EOFL) alternatives for such batteries. In addition to the current state, trends for future technological development are presented.

Within part A, chapter 2 focusses on the production side of batteries. Included are a section on battery composition with a focus on the different cell chemistries, followed by an analysis of origin of and concern about the various raw materials used in LIBs. Then, the battery manufacturing process is presented, and the chapter closes with an overview of the legislative framework for the battery value chain in the EU. Chapter 3 analyses the EOFL alternatives for automotive batteries. Different potential routes for EOL battery treatment are presented, whereas the focus is on the state-of-the-art in recycling and reuse of LIBs. The different approaches are assessed both from an ecological and an economical point of view. Together, chapter 2 and 3 establish the baseline for the scenario modelling.

Part B of the thesis presents the methodology and results of the scenario modelling and consists of 2 chapters.

Chapter 4 presents the approach of the analysis and its limitations for each of the four scenario dimensions: battery lifetime, raw materials, second life and recycling. Thereafter, chapter 5 presents the results of the analysis and its implications on battery demand and supply, volume of EOL batteries, the recycling industry and second life applications. Based on the results, political implications are discussed.

As the final part of the thesis, chapter 6 provides a summary of the findings and suggests areas for future work.

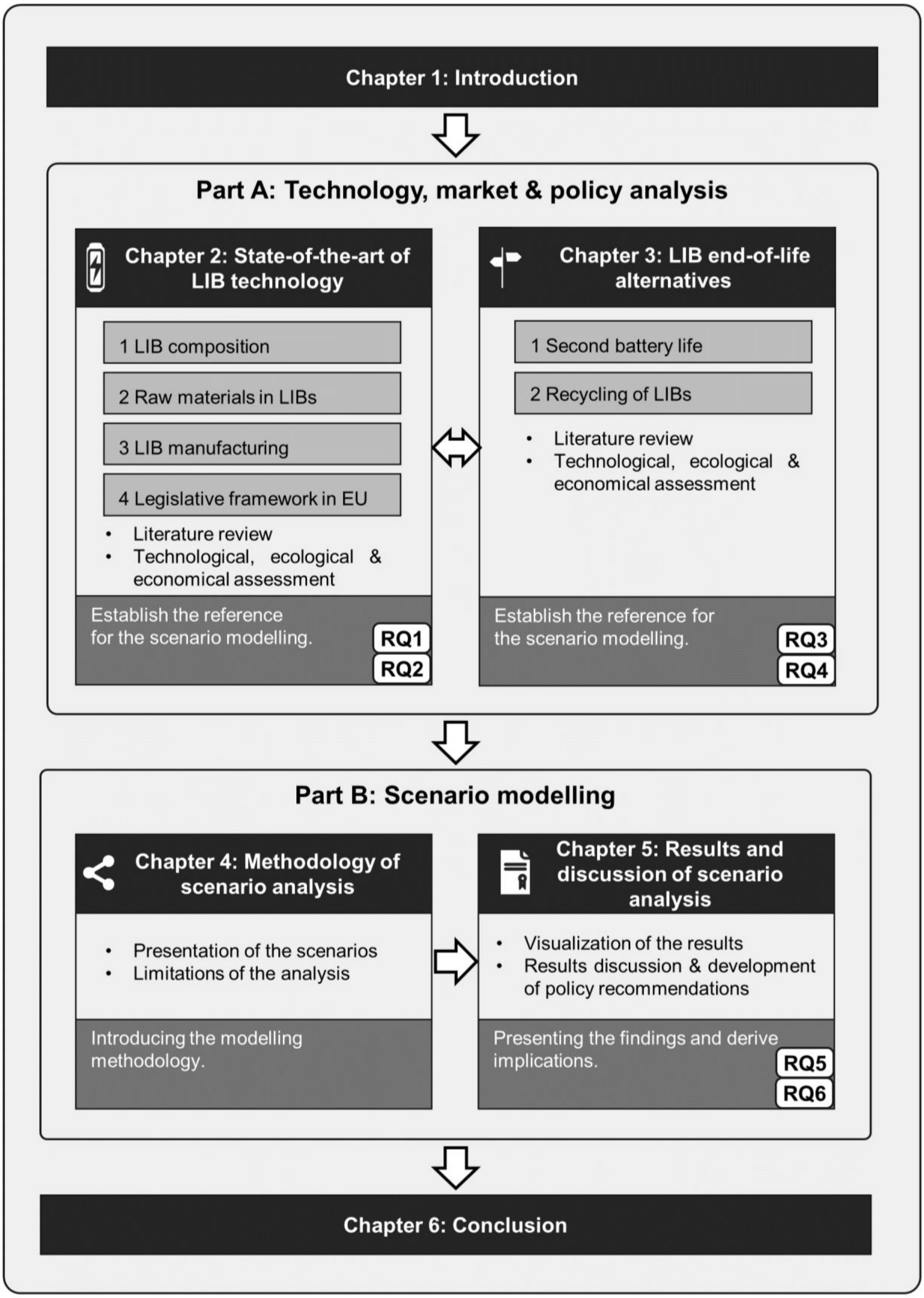


Figure 1.2.1 Content and relationships between different chapters of the thesis.

2 State-of-the-art of lithium-ion battery technology

Since their commercialization by Sony Co. in 1991, rechargeable LIBs have become the dominating battery type used in EVs around the world. Their success can be attributed among others to the higher energy density compared to other types of batteries like Nickel-Cadmium (NiCd) or Nickel-Metal Hydride (NiMH) (Li et al. 2018). The importance of LIBs for modern society was recently underlined when the 2019 Nobel prize in chemistry was awarded to three scientists "for the development of lithium-ion batteries".

This chapter will analyze the state-of-the-art of lithium-ion battery technology. The battery composition of two state-of-the-art high performing LIB types (NMC622 and NCA[5]) is presented to identify the core elements that constitute a battery and create a mass balance as the basis for the scenario analysis. Battery raw materials are assessed with a focus on price development, sustainability of production and supply risks. Thereafter, the economics and the environmental impacts of LIB manufacturing are analyzed. The last part of this chapter discusses the political strategy of the EU and presents the regulatory framework that impacts the battery value chain.

2.1 Lithium-Ion battery composition

2.1.1 Overview

The main components of LIBs are electrodes (positive and negative), current collector (for positive and negative electrode), separator, electrolyte, and casing. The voltage of the battery derives from the difference in electric potential between the chosen pair of electrode materials, and the theoretical capacity is determined by the properties of each electrode material. The cell voltage of modern LIBs is commonly around 3,6 V and the energy density at an average of 200 Wh kg^{-1} (gravimetric) and 400 Wh L^{-1} (volumetric) (Thielmann et al. 2020).

The name-giving component, lithium, known as the lightest among all metals (0,53 g/cm^3), is chosen as the insertion material for the electrodes due to its small atomic radius that results in a high diffusion coefficient (Li et al. 2018). During discharge, lithium-ions (Li^+) move from the anode material through the separator and are intercalated into the lattice of the cathode material (see Figure 2.1.1). Simultaneously, electrons move through the external circuit and can be utilized if a load is connected. Electrodes and separator are immersed in an electrolyte, a conductive and (in the case of LIBs) non-aqueous solution that facilitates the transport of Li^+. The separator is a membrane that is permeable for Li^+ but together with the electrolyte prevents the direct exchange of electrons between the two sides.

[5] With a molar fraction of NCA materials in the cathode of 92% nickel, 5% cobalt, and 3% aluminium.

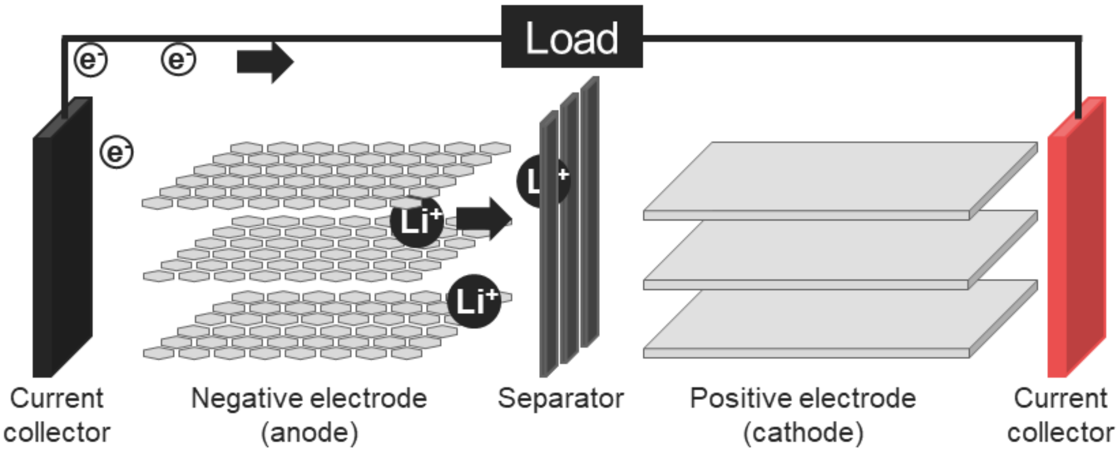


Figure 2.1.1 Scheme of a LIB cell during discharge.

LIBs have become the preferred choice for EVs due to their superior properties compared to alternatives like NiCd (formerly used in some hybrid electric vehicles like the Honda Insight in the late 1990s) or NiMH (used in several hybrid electric vehicles today, like the Toyota Yaris Hybrid) (Li et al. 2018). The advantage of LIBs come in its high specific energy and power, and long calendar and cycle lives. Disadvantages result from the high chemical reactivity of lithium (which causes safety concerns) as well as from the costs due to the use of high-priced raw materials like cobalt or nickel (Zubi et al. 2018) (Kurzweil 2015).

The following subchapters will give further information on the LIB components, with a focus on choice of materials, composition, and future development. Estimations of material distribution on cell level are compared between a NMC622 and an NCA battery (in kg/kWh values, visualized as colored bar charts).

2.1.2 Cathode

The positive electrode consists of a lithium metal oxide, a lattice of different metals in which Li-ions can be intercalated. The evolution of cathode chemistries since the LIB commercialization shows changing material composition and a trend towards higher performing designs. Early cathodes were composed of lithium cobalt oxide ($LiCoO_2$, short: LCO), as used for the Nissan Altra in 1997 (Li et al. 2018). To reduce the price, cobalt was substituted by iron phosphate ($LiFePO_4$, short: LFP) or manganese ($LiMn_2O_4$, short: LMO) (Julien et al. 2016). Disadvantages of these changes come in reduction of specific energy. Applications such as electric buses offer more installation space and thus the lower energy density is less problematic and LFP batteries are widely used due to their low cost and high stability (Li et al. 2018). EV batteries for passenger cars on the other hand require a high volumetric energy density to meet the customers' expectations of a sufficient driving range. Thus, a blend of cobalt with other metals is commonly used in EV LIBs today. Such blend can consist of nickel, cobalt, and aluminum ($LiNiCoAlO_2$, short: NCA) or nickel, manganese, and cobalt (LiNiMnCo, short: NMC). High nickel amounts, used in both modern NCA and NMC cathodes, significantly improve the discharge capacity, but at the same time they reduce thermal stability (Li et al. 2018). NCA and NMC based LIBs dominate the EV market today and are used by a variety of automakers. Table 2.1.1 shows a list of the most selling passenger car EV models in Germany in 2019 with their respective LIB cathode types.

Table 2.1.1 Battery producer and cathode type of most selling EV models in Germany in 2019.

Number of EV sales	Battery producer	EV company and model	Cathode material
9.431	LG Chem	Renault Zoe	NMC622
9.117	SDI	BMW i3	NMC622[6]
9.013	Panasonic	Tesla Model 3	NCA
6.898	SDI	VW Golf	NMC532

Data based on: (KBA 2020) (Takeshita et al. 2019)

NCA based batteries were early adopted by Panasonic in small cylindrical cells for usage in Tesla vehicles and a common material distribution in the cathode was a mix in molar fractions comprised of 80% nickel, 15% cobalt, and 5% aluminium ($LiNi_{0,8}Co_{0,15}Al_{0,05}O_2$) (Lai et al. 2016). Nickel contents have by then increased while cobalt contents dropped to as low as 5% molar fraction ($LiNi_{0,92}Co_{0,05}Al_{0,03}O_2$) (Takeshita et al. 2016).

NMC based cathodes consist of a lithium oxide blended with nickel, manganese, and cobalt. While nickel and cobalt guarantee the electronic conductivity, manganese increases the structural stability (Oh et al. 2019) and furthermore reduces costs. To increase the performance of NMC cathodes further and reduce dependence on cobalt (due to supply risk and high and fluctuating market prices), nickel contents are gradually increasing. Starting from an equal distribution (molar fraction) of nickel, manganese and cobalt ($LiN_{0,33}M_{0,33}C_{0,33}$, commonly referred to as NMC111), the composition changed to 50% and 60% nickel share (NMC532 and NMC622), and today EV batteries with 80% nickel share (NMC811) start entering the market. Problems of replacing cobalt with nickel are seen in decreased cycle stability, therefore a completely cobalt-free system will most likely require the usage of another third transition metal (Li and Lu 2020).

The shift towards higher nickel content cathodes is visualized in Figure 2.1.2, showing an analysis of 147 launches of new models of passenger car EVs from 2017 to 2021 with a clear trend towards higher nickel contents in NMC based battery cathodes. Of the EV models under analysis, the South Korean battery manufacturer LG Chem was the first cell supplier to introduce the NMC622 cathode in 2017, and CATL (Chinese) and SKI (South Korean) were the first to start supplying NMC811 LIBs in 2019.

[6] before 2019: NMC532

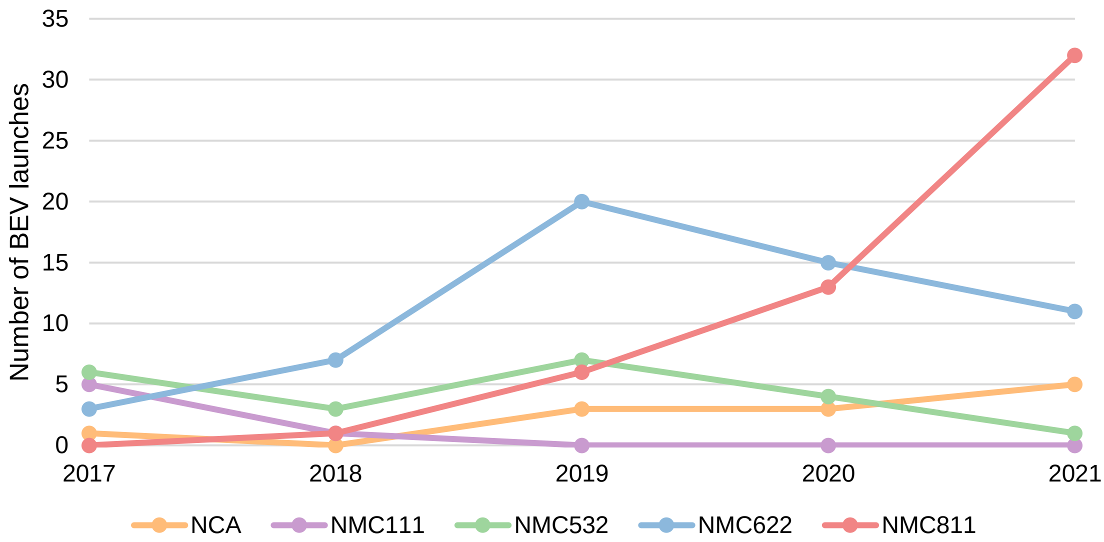


Figure 2.1.2 Cathode chemistries of LIBs from 147 passenger car BEV model launches between 2017 and 2021 (actual and announced).

Own calculation based on: (Takeshita et al. 2019)

To create a functioning LIB cathode, further materials are added to the slurry during production to create the desired properties. Conductive additives such as carbon black (CB) or acetylene black (AB) are used to increase conductivity, whereas a binder, commonly polyvinylidene fluoride (PVDF), provides structural stability (Julien et al. 2016). Mixed with conductive additives and binder, the active materials are coated on the current collector, made of aluminium foil. Table 2.1.2 shows an estimated material mass balance for a NMC622 and NCA ($Ni_{0,92}Co_{0,05}Al_{0,03}$) cathode.

Table 2.1.2 Estimated mass balances for cathode and current collector of a LIB cell.

		kg/kWh	
Material	**Function**	**NMC622**	**NCA**
Lithium carbonate (Li_2CO_3)	Active material	0,586	0,520
Nickel	Active material	0,558	0,760
Manganese	Active material	0,174	-
Cobalt	Active material	0,187	0,041
Aluminium	Active material	-	0,011
AB	Conductive additive	0,069	0,018
PVDF	Binder	0,045	0,012
Al foil	Current collector	0,126	0,104
		1,745	**1,466**

Own calculation based on: (Takeshita et al. 2016, 2018)

Several future developments of LIB cathodes are currently under research. For example, coating of the cathodes is expected mitigate the problem of increased reactivity of modern LIBs. Further developments are also foreseeable in the production process. Microstructure optimization such as increasing the thickness of the active material layer results in a higher energy density, but further research is needed on how to avoid the lowering of the conductivity.

During the production process an organic solvent such as N-methyl pyrrolidone (NMP) is added to the slurry and later removed during the drying steps. The sustainability of the production process would be increased if toxic solvents such as NMP are substituted with water, whereas challenges come with a higher energy demand of the production process and battery performance problems (Thielmann et al. 2017). Future cathode production could also be done without the use of solvents at all. In 2019, Tesla acquired the company Maxwell Technologies, who developed a dry electrode coating technology, which can completely eliminate the use of solvents and furthermore avoids the time consuming drying steps (Duong et al. 2018).

2.1.3 Anode

In contrast to the material variations in the cathode, the negative electrode is nearly always made of graphite (C_6), since carbon has a high electrical capacity and shows a reversible lithiation process (Li et al. 2018). Even though prices for natural graphite are low compared to cathode materials, it was listed as one of the critical raw materials by the EU in 2020 due to the high EU import dependency (Huisman et al. 2020).

During the production process, a binder such as carboxymethyl cellulose (CMC) or styrene-butadiene rubber (SBR) is added to the active material before the mix is coated on the current collector made of copper foil. An estimated mass balance for the anode materials can be seen in Table 2.1.3.

Table 2.1.3 Estimated mass balance for anode and current collector of a LIB cell.

		kg/kWh	
Material	**Function**	**NMC622**	**NCA**
Natural graphite	Active material	0,908	0,926
CMC/SBR	Binder	0,030	0,028
Copper foil	Current collector	0,417	0,260
		1,354	**1,214**

Own calculation based on: (Takeshita et al. 2016, 2018)

Regardless of the import dependency of graphite, research is less focusing on replacing graphite but rather on creating composites by adding silicon to increase the specific capacity. Silicon by itself is prone to large volume changes during the lithiation process, leading to fast material degradation and reduction in performance, whereas a graphite silicon composite can use the benefits of both materials. Such composites with low shares of silicon (<5%) are already in use in a variety of EVs such as Tesla's model 3, whereas in the future the share of silicon is expected to increase further (Thielmann et al. 2017) (Takeshita et al. 2019).

2.1.4 Electrolyte and separator

The electrolyte must have good ionic conductivity to allow for a high transport rate of Li^+ (Jow et al. 2014). In contrast to older battery technologies like lead-acid or NiMH who use a water-based electrolyte, LIBs work with a non-aqueous electrolyte. By avoiding the use of water, the operating voltage can exceed those of lead-acid or NiMH batteries, for which high voltages will cause water electrolysis. LIBs can operate on voltages up to 4 V without electrolyte damage.

To create the electrolyte, a lithium salt such as lithium hexafluorophosphate ($LiPF_6$) is mixed with a liquid solvent and further additives. The liquid solvent can be composed of different carbon-based compounds, such as ethylene carbonate (EC) or dimethyl carbonate (DMC). Additives, such as vinylene carbonate (VC) are used to enhance the performance and increase safety, whereas specific information on number and composition of additives in modern LIB electrolytes remain company secrets (Jow et al. 2014).

The separator is located between the two electrodes and prevents their physical contact. It consists of a thin, porous layer made of polyolefin membranes such as polyethylene (PE). The membrane offers ionic conductivity while insulating any electronic flow (Julien et al. 2016). An estimated material composition for electrolyte and separator is shown in Table 2.1.4.

Table 2.1.4 Estimated mass balance for electrolyte and separator of a LIB cell.

Material	Function	kg/kWh NMC622	kg/kWh NCA
EC/DMC	Electrolyte solvent	0,476	0,348
$LiPF_6$	Lithium salt	0,077	0,057
PE	Separator	0,139	0,093
		0,692	**0,498**

Own calculation based on: (Takeshita et al. 2016, 2018)

Future improvements on stability and performance can be expected through additional optimization of electrolyte additives and creating thinner but stable separators through applying ceramic coatings. Research is furthermore investigating the use of solid electrolytes to improve safety, whereas this approach is still at a low technology readiness level (TRL) (Thielmann et al. 2017).

2.1.5 Casing

The casing seals the LIB from the environment. Commonly, three different assembling approaches are used (cylindric, prismatic, and pouch) each resulting in a different cell geometry of the LIB (Figure 2.1.3).

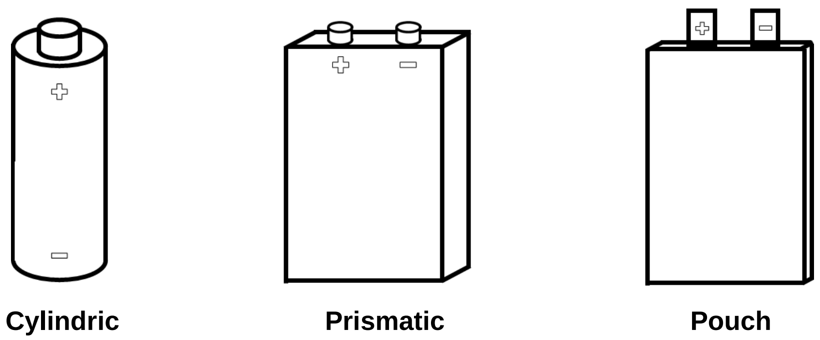


Figure 2.1.3 Different LIB cell geometries.

Cylindrical cells are used in EVs made by Tesla and have a low production cost. The design requires a stable metal casing (Hettesheimer 2017), and due to the small size of each individual cell, thousands of cells are required to reach the capacity to power an EV. The small cell size can furthermore hamper the second life usage of such batteries due to the low energy density of individual cells and the need for complex dismantling (Reid and Julve 2016).

Like in the cylindrical design, prismatic cells have a robust casing, but are rectangular in shape and thus can be stacked efficiently with minimal space loss between cells (Weicker 2014). The large surface area provides good thermal dissipation properties (Hettesheimer 2017) and the higher capacity per individual cell favors second use applications (Reid and Julve 2016).

Pouch cells are characterized by their light casing (pouch) made of e.g. a polymer coated aluminium and protruding metallic tabs. The large surface area allows for good heat dissipation and the flat design enables efficient stacking. The low mechanical stability must be compensated through stable design on module level (Hettesheimer 2017).

Figure 2.1.4 shows the cell shape for the LIBs of the same 147 EV launches presented in Figure 2.1.2. Cylindrical cell shapes prevail in NCA batteries, while NMC batteries predominantly use pouch or prismatic cells with an expected rise of pouch cells in upcoming years. Of the EVs under analysis, the cell manufacturers LG Chem and AESC were the first to use the pouch design for their NMC LIBs in 2017, while other suppliers such as SDI and CATL continue to favor the prismatic shape.

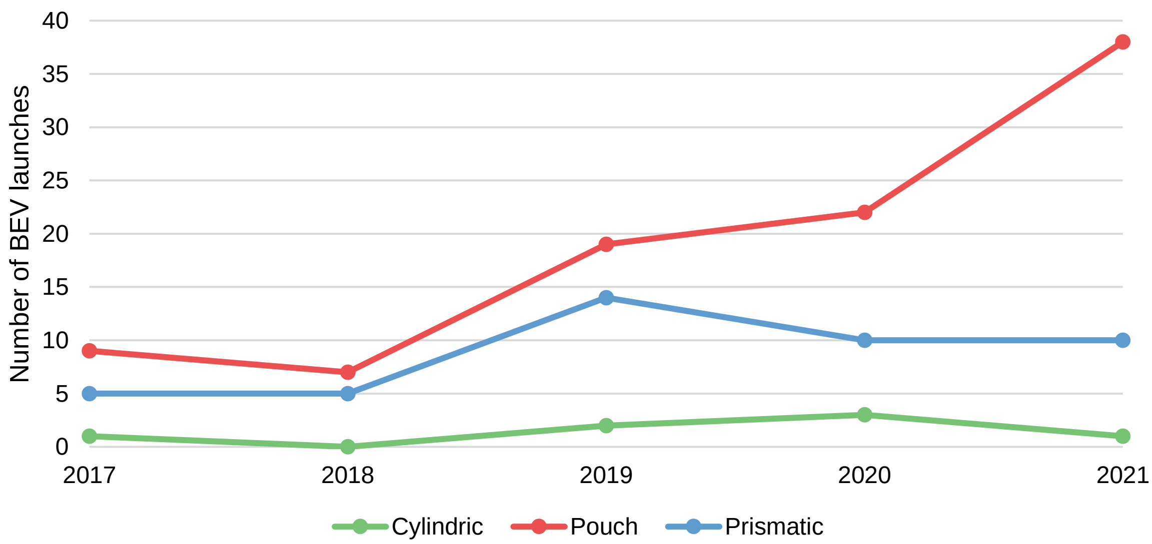


Figure 2.1.4 Cell shapes of LIBs from 147 EV model launches between 2017 and 2021 (actual and announced).

Own calculations based on: (Takeshita et al. 2019)

For both prismatic and pouch cells, costs are currently higher and energy density is lower than for cylindrical cells (Thielmann et al. 2017). To some degree, these disadvantages are mitigated on the system level through more efficient stacking with less dead volume. Table 2.1.5 lists the estimated mass balance for an NMC622 LIB cell with a pouch and an NCA LIB cell with cylindrical casing.

Table 2.1.5 Estimated mass balance for casing of a LIB cell.

Material	Function	kg/kWh Pouch	kg/kWh Cylindric
PET/Al laminate + Al/Ni tab	Case	0,153	-
Ni plated Fe + top cover	Case	-	0,682
		0,153	**0,682**

Own calculation based on: (Takeshita et al. 2016, 2018)

2.1.6 Modules and packs

To achieve the required energy capacity, individual LIB cells are grouped into modules, equipped with a cooling system, and protected by a casing. Several modules are then combined into a battery pack, controlled with a battery management system (BMS). Module and pack packaging provide structural stability, whereas the cooling system and the BMS guarantee safety and optimal performance.

The BMS monitors and controls the functionality of the battery system, by measuring operating data such as temperature, current and voltage. It controls and balances the rate of charge to avoid overstressing individual cells and thus significantly influences the lifetime and operation safety of the battery (Hettesheimer 2017) (Weicker 2014).

For the entire battery pack of a 60 to 80 kWh EV battery system made of pouch cells, the cells make up approximately 75% of the weight (Figure 2.1.5), while module and pack elements account for 5% and 19% respectively (own calculations based on (Nelson et al. 2019)). The advantages of NCA batteries in volumetric energy density on the cell level are offset on system level through higher dead volumes due to the circular cell shape (Thielmann et al. 2017).

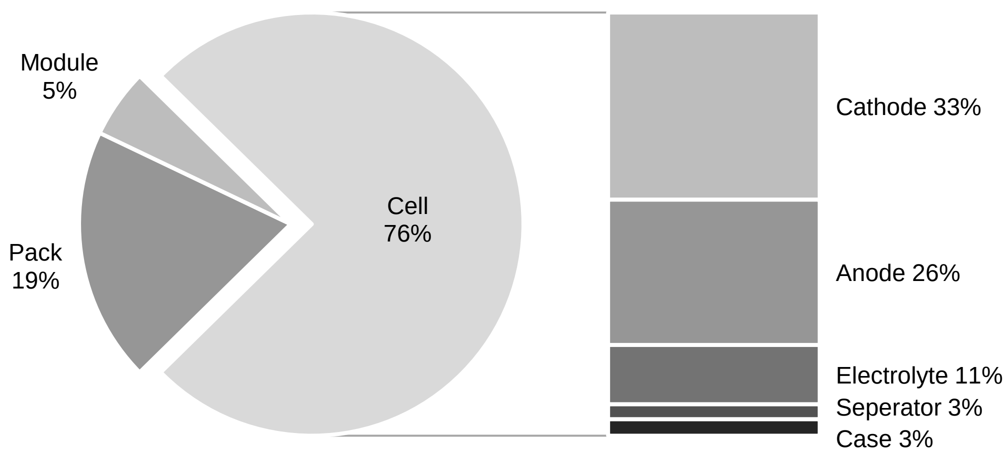


Figure 2.1.5 Estimated mass balance for a 60 kWh battery system, made of NMC622 pouch cell LIBs.

Own calculation based on: (Takeshita et al. 2016, 2018), (Nelson et al. 2019)

Additional to materials in the battery cells, the modules and pack require metals and plastics for casing, as well as wiring and other electronic elements for interconnection of cells and controlling. By improving the monitoring on system level, performance and lifetime could be increased in the future, e.g. through balancing cell temperatures to achieve uniform aging curves of the individual cells and thus a longer lifetime of the battery system (Thielmann et al. 2017).

Furthermore, it is expected that battery modules and packs will be reduced in weight. In January 2020, Tesla CEO Elon Musk announced the idea to remove modules and group cells directly into packs (CleanTechnica 2020). Such an approach could drastically increase the energy density but could lead to problems in both safety and maintenance.

2.1.7 Outlook

Since the commercialization of LIBs in 1991 the technology has seen rapid improvements in power density, safety, and a reduction in costs. The state of the art for EVs is a high performing battery such as NMC622 or a high nickel NCA, whereas nickel contents are expected to rise further and in upcoming years NMC811 batteries will become the dominating battery type for manufacturers other than Tesla. Other LIB components show less material variation when compared to the cathode. State-of-the-art anodes are graphite based, the electrolyte is comprised of a lithium salt and various liquid solvents, and the separator is made of a polyolefin membrane. All components will see further enhancements of performance through e.g. improving additives (electrolyte), ceramic coatings (separator), or blending different materials to create higher performing composites (silicon anode). While Tesla EVs are using cylindric cells, other automakers favor prismatic or pouch cells. A trend was detected towards using the lighter casing pouch cells.

2.2 Raw materials in lithium-ion batteries

A variety of metallic and non-metallic raw materials are needed to produce a state-of-the-art LIB cell. These materials show considerable differences in the three dimensions of economics, political relevance for the EU, and environmental impact. In the economic dimension, the prices of the raw materials are impacting both the selling price of the battery and the potential revenues and thus feasibility of recycling. For the environmental dimension, the focus lays on the emissions associated with mining and refining of the raw materials. The political relevance of materials is determined by both supply risks and social concerns within the supply chain which causes governments to impose regulatory elements. Out of the materials used in the base case battery, cobalt, natural graphite and lithium are classified as critical raw materials by the EU (Eynard et al. 2020a), due to their high overall economic importance and high supply risk.

Based on the state-of-the-art NMC622 battery (subchapter 2.1), Figure 2.2.1 lists on the left the material composition of the battery system on a mass per kWh basis. The right side of the graph shows the average monthly price development for all the metals within the battery system and graphite.

In the following subchapter, the methodology for the assessment of market prices, environmental impacts and supply risk are presented. Thereafter, economics, political relevance, and environmental impact are discussed in further detail for core materials withing the LIB system. Due to their high weight share and importance for the economics of recycling, only the metals and graphite will be discussed (colored items in Figure 2.2.1).

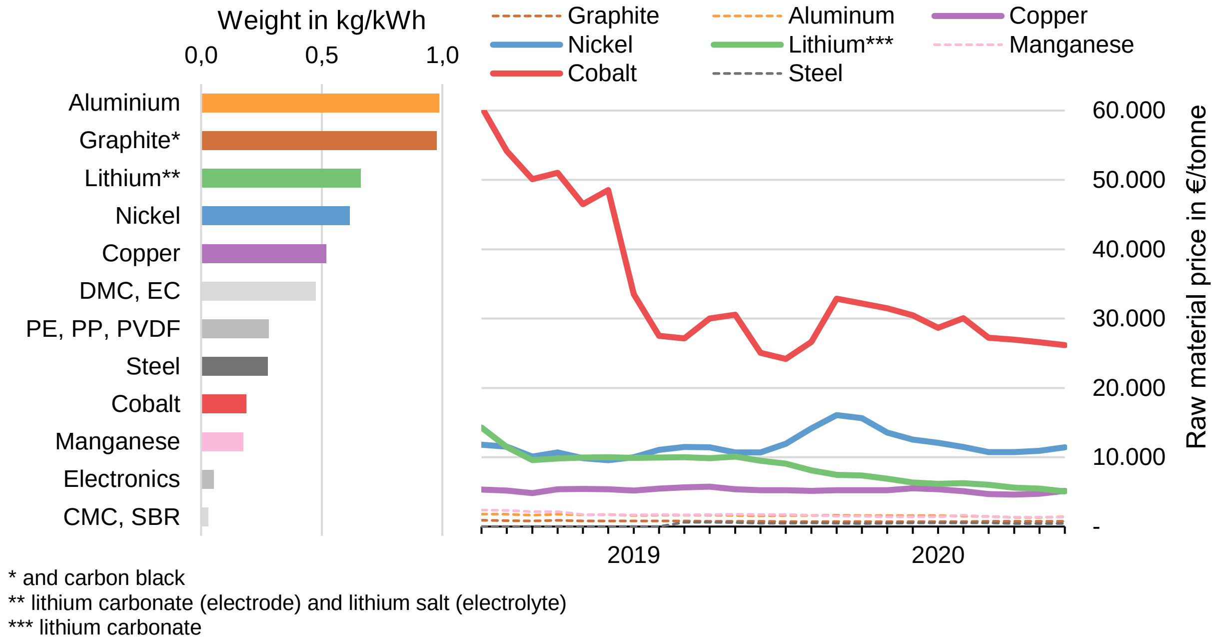


Figure 2.2.1 Mass balance for a NMC622 battery pack (left) and raw material price development from July 2018 to June 2020 (right) [7].

Own calculation based on: (Takeshita et al. 2019), (DERA 2020; LME 2020)

2.2.1 Methodology

Market prices were collected from reports of the German Mineral Resources Agency (DERA) and originate from European and international metal markets (DERA 2020), and are expressed as the median of average monthly market prices for January to December 2019 (see Annex Table A.8).

The environmental assessment is based on the Product Environmental Footprint (PEF) database made available by the European Union and utilizes data that was part of the Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications, with data validity until 2020 (Bonell et al. 2018). Underlying database for the environmental impacts is Ecoinvent and calculations are performed using the open source software OpenLCA version 1.10.2. Methodology for the impact assessment is the EU environmental footprint impact assessment (European Commission 2010) for the impact category climate change (based on the baseline model of the Intergovernmental Panel on Climate Change (IPCC) 2013 and factors adapted from the Environmental Footprint guidance). The impact on global warming in this chapter solely covers the raw material production process (excluding transport and battery production). Additional values for environmental impacts of raw materials were found in the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET) developed by Argonne National Laboratory (Wang

[7] In the material price graph on the right, four materials (graphite, aluminium, manganese and steel) are at the bottom of the line chart with prices below 2.000 €/tonne. The purpose of the graph is to visualize the absolute differences in material prices and show which materials have the greatest economic impact within the LIB. Therefore, it was accepted that no distinctions among the lower priced materials (graphite, aluminium, manganese and steel) can be made.

2019) and sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. GREET can be downloaded as an Excel spreadsheet that allows the individual adjustment of values within the life cycle analysis.

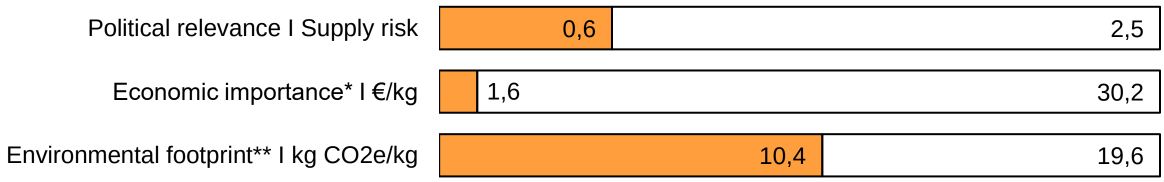
The median between PEFCR value and GREET values was calculated to generate more robust results and not rely on a single source of information.

The assessment of political relevance uses data from the EU's list of critical and non-critical raw materials from 2020 (Eynard et al. 2020a). Therein, the supply risk is evaluated using various parameters including the Herfindahl-Hirschman Index (for country/market concentration), import reliance, end-of-life recycling input rate and substitutability related to supply risk (Baranzelli et al. 2017) (see Annex Table A.9).

In the following subchapters, each material is assessed in the environmental, economic, and political dimension. A horizontal bar chart is used to plot the supply risk, the market price, and the CO_2 footprint, respectively for each material against the maximum of all the materials under consideration.

2.2.2 Aluminium

Aluminium is used as the cathode current collector and as a structural element for cell casing, modules, and pack. A high share of aluminium production is based in China (47% of worldwide aluminium production in 2016 (Eynard et al. 2020a)), but bauxite[8] reserves are dispersed around the continents (Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%)) and are abundant enough to meet global demand well into the future (USGS 2020). Furthermore, aluminium is recyclable without loss of performance (European Commission 2017b). Thus, the supply risk of aluminium is low. Likewise, as seen in Figure 2.2.2, aluminium is a cheap trade good compared to the other battery materials. At the downside, the environmental footprint of primary aluminium is very high (third highest) due to the high energy demand for the production process, making recycling a desirable option (Gautam et al. 2018).



* Median for the year 2019. Commodity: high grade primary aluminium, in London Metal Exchange (LME) warehouse.
** Median of PEFCR and GREET values. PEFCR: aluminium sheet production & aluminium foil production, both EU-28+European Free Trade Association (EFTA); GREET: virgin wrought aluminium and virgin cast aluminium

Figure 2.2.2 Economic, political and ecological assessment of aluminium per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

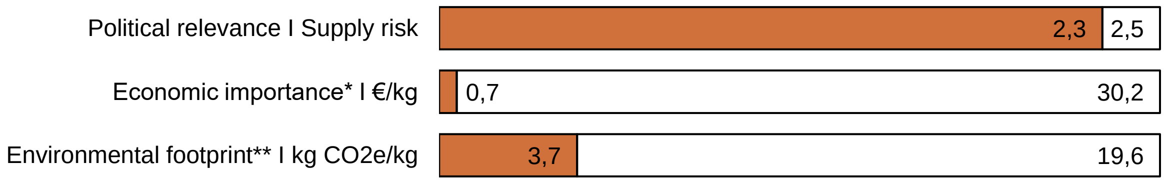
Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

[8] Primary raw material used to produce aluminium metal. Sedimentary rock with high aluminium content.

2.2.3 Natural graphite

Graphite is used in large quantities as the anode material of LIBs. In its natural form, graphite is part of EU's list of critical raw materials, especially due to the high supply risk with 98% import reliance (Eynard et al. 2020a). Global reserves and production capabilities are concentrated predominantly in China, who controls 70% of global production (Huisman et al. 2020). Other countries with shares of global graphite reserves similar or exceeding those of China are Turkey and Brazil, whereas the exploration rate is still low in both countries (USGS 2020).

Of global natural graphite production, about 10% are used in the anode manufacturing process. While supply risk of natural graphite is high, synthetic graphite is a more costly but appropriate substitute. Like natural graphite, synthetic graphite production is currently concentrated mainly in China. To reduce import dependency, several projects within Europe are exploring domestic graphite mining (10 projects as of December 2018) (Huisman et al. 2020). Due to the trend of diversification of global suppliers the supply risk of natural graphite was lowered compared to the 2017 EU list of critical raw materials. After being the material with the highest supply risk in 2017, natural graphite is now only the material with the second highest value after cobalt (Figure 2.2.3).



* Median for the year 2019. Commodity: Crystalline large flake graphite, European port.
** Median of PEFCR and GREET values. PEFCR: carbon black production, Europe; GREET: graphite.

Figure 2.2.3 Economic, political and ecological assessment of natural graphite per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

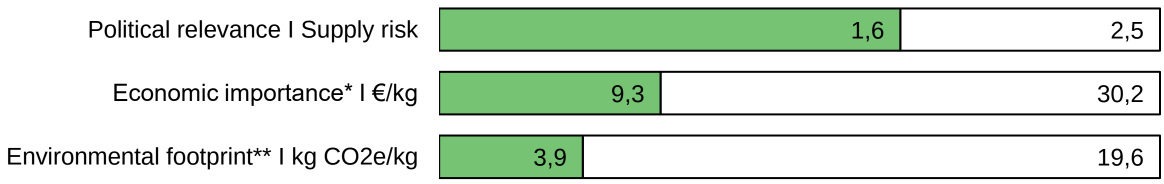
As shown in Figure 2.2.3 natural graphite has both a low environmental footprint (third lowest value) and a low market price (second lowest value) compared to the other battery materials.

As described in subchapter 2.1.3, EV makers are starting to introduce silicon into the anode materials, thus reducing the share of graphite. It should be noted that silicon is like natural graphite classified as critical, with an even greater economic importance for the EU but a lower supply risk.

2.2.4 Lithium

As the name giving material, lithium is also among the LIB materials which attract the highest media attention and in September 2020 it was added to the list of critical raw materials for the EU (Eynard et al. 2020a). Prices for lithium carbonate (Li_2CO_3), the market commodity of lithium, are the third highest among the eight LIB raw materials under consideration (Figure 2.2.4), only exceeded by nickel and cobalt. The supply risk of lithium is the third highest, but lower than natural graphite and cobalt, due to the variety of countries that supply lithium and the large known reserves.

A car fleet of 1 billion 60 kWh EVs that use a state-of-the-art NMC622 LIB would require below 40 million tons of lithium carbonate which equals 7,5 million tons of pure lithium metal, a value far from the estimated 80 million tons of global lithium resources (USGS 2020).



* Median for the year 2019. Commodity: Lithium carbonate battery grade, China.
** Median of PEFCR and GREET values. PEFCR: lithium carbonate production & lithium hydroxide production, both global; GREET: LiPF6.

Figure 2.2.4 Economic, political and ecological assessment of lithium per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

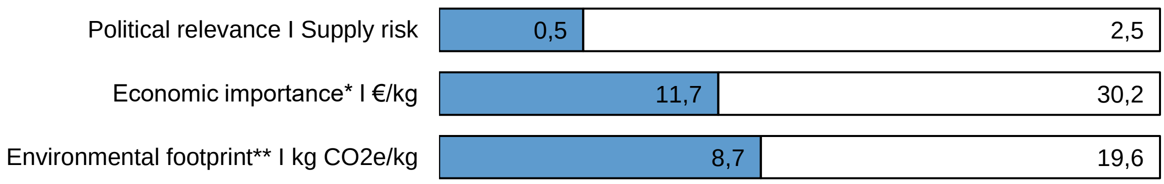
Estimated resources are largest in Latin America, due to the concentration of lithium brines in the so-called lithium triangle, comprised of Bolivia (21 million tons), Argentina (17 million tons) and Chile (9 million tons). Many of those sources are still unexploited, and currently Australia (6,3 million tons) is the country that supplies most lithium to the market. Lithium reserves can furthermore be found in a variety of EU countries, including Czechia, Finland, Germany, and Portugal (Eynard et al. 2020a).

While there is currently no domestic European lithium production, 14 mining projects are under evaluation or construction. Nevertheless, such projects can be hampered by falling lithium prices. As seen in Figure 2.2.1, lithium carbonate prices decreased significantly in 2019 caused by an overproduction (USGS 2020). To build a domestic European lithium supply chain, not only mines, but also refining facilities need to be established. Currently, China holds 45% of lithium hard-rock refining facilities (USGS 2020) (Huisman et al. 2020).

Compared to the other LIB materials, the CO_2 footprint for lithium carbonate production from brines is very low (second lowest). GHG emissions double if the lithium carbonate is further refined via chemical reaction to lithium hydroxide (LiOH), which is increasingly replacing carbonate in the battery manufacturing process (Huisman et al. 2020) (GreenDelta GmbH 2020). Since European lithium is mainly found in hard rocks, a domestic production can be expected to have a poorer ecological balance due to the energy intensive extraction process which includes crushing of rock and use of hydrometallurgical processes. In the lithium triangle the material is extracted from brines (highly saline solutions) by using evaporitic technology, in which the brine is pumped in open air ponds where the solar evaporation occurs. This technology causes very low environmental impacts, although the water demand in the normally arid land is of concern (e.g. fresh water demand for purification steps) (Flexer et al. 2018).

2.2.5 Nickel

Nickel is of special interest due to its high price (second highest). It is the material with the largest share of total cell costs due to the large amount of nickel inside a LIB cell. Nevertheless, nickel is increasingly replacing cobalt in the cathode material mix since its price is still lower than that of cobalt and the supply risk of nickel is very low due to the diversity of suppliers. In 2019, production was located in a variety of countries such as Indonesia (800.000 tons), Philippines (420.000 tons), Russia (270.000 tons) and Australia (180.000 tons) (USGS 2020). In the EU there are 10 domestic production locations and 10 locations under development. Similar to lithium, much of the global refining capacities are concentrated in China (30%) (Huisman et al. 2020). The environmental footprint in terms of GHG emissions is similar to that of aluminium and caused by the high energy demand for smelter and refinery (see Figure 2.2.5).



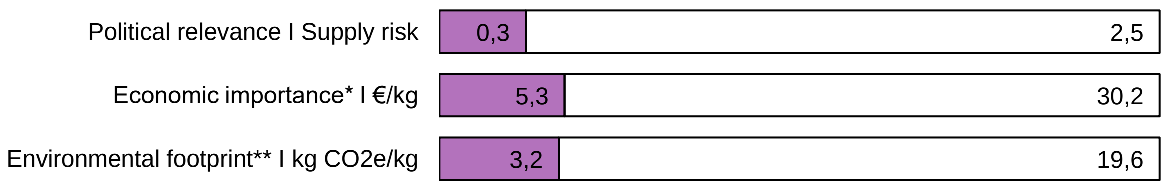
* Median for the year 2019. Commodity: Min. 99,8% nickel, in LME warehouse.
** Median of PEFCR and GREET values. PEFCR: nickel production, global; GREET: virgin nickel, virgin nickel hydroxide.

Figure 2.2.5 Economic, political and ecological assessment of nickel per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

2.2.6 Copper

Copper functions as the current collector in the anode and is furthermore used in the BMS. Market prices for copper are in the medium range of the materials under consideration and the supply risk is very low due to the variety of suppliers. In 2019, production was estimated at 20 million tons, with 5,6 million tons supplied to the global market by Chile, 2,4 million tons by Peru and 1,6 million tons by China. The environmental impact of copper is comparatively low (Figure 2.2.6).



* Median for the year 2019. Commodity: grade A copper, LME warehouse.
** Median of PEFCR and GREET values. PEFCR: copper oxide; GREET: copper.

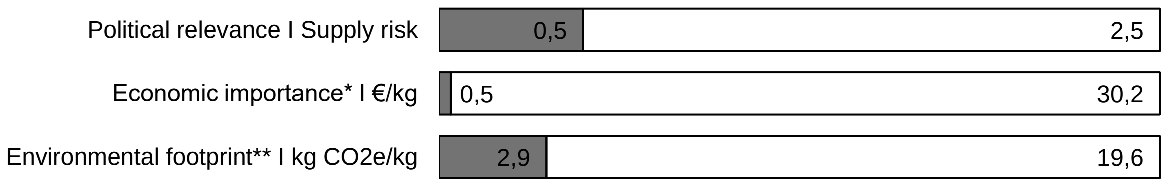
Figure 2.2.6 Economic, political and ecological assessment of copper per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

2.2.7 Steel

Steel is used as a structural element for LIB module and pack design. It is produced from iron ore, which is abundant in the earth's crust and distributed around all continents, therefore the supply risk is comparatively low. Estimated iron reserves are highest in Australia, followed by Brazil and South Africa. Raw steel production is dominated by China (1 billion tons in 2019), but a variety of other countries produce it as well, including Japan (100 million tons), India (110 million tons) and the US (87 million tons) (USGS 2020). Highest European production of raw steel in 2019 was in Germany (41 million tons). Overall, there are more than 500 steel production sites across EU Member States (European Commission 2017b).

Out of all materials under consideration, steel's average market price in 2019 was the lowest at 497 €/ton (US HRC steel) (Figure 2.2.7). Furthermore, steel production from iron ore causes little emissions compared to most of the other metals (third lowest value).



* Median for the year 2019. Commodity: Hot rolled coiled steel (HRC) steel, north America.
** Median of PEFCR and GREET values. PEFCR: Cold rolled coil steel, EU-28+EFTA; GREET: virgin steel and cast iron.

Figure 2.2.7 Economic, political and ecological assessment of steel per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

2.2.8 Cobalt

Cobalt is the most critical raw material in a LIB due to its by far highest market prices, largest environmental footprint and since 2020 highest supply risk (Figure 2.2.8). It is one of the active materials in the cathode and essential for the stability of high-density LIBs (Oh et al. 2019). Nevertheless, due to the high and volatile price, battery producers are reducing the share of cobalt to a minimum.

* Median for the year 2019. Commodity: min. 99,8% cobalt, LME warehouse
** Median of PEFCR and GREET values. PEFCR: cobalt production, global; GREET: virgin cobalt -oxide, -chloride and -metal

Figure 2.2.8 Economic, political and ecological assessment of steel per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on : (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

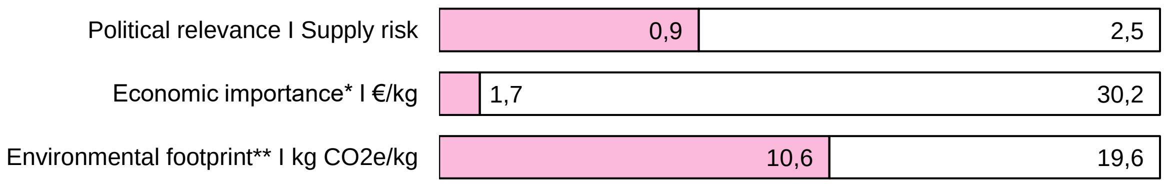
Cobalt is extracted as a by-product of nickel or copper mining and 70% of global production in 2019 was mined in the Democratic Republic of Congo (DRC). Estimated reserves are also largest in the DRC (3,6 million tons), followed by Australia (1,2 million tons) and Cuba (0,5 million tons) (USGS 2020). In addition to the uneven distribution of resources and production capacity, cobalt prices have seen strong fluctuations in recent years. Prices peaked in early 2018 but fell strongly afterwards (InvestmentMine 2020). In 2019 prices stabilized between 30.000 and 40.000 €/tonne (DERA 2020), but they are still showing the largest fluctuations of all LIB raw materials (see Figure 2.2.1).

A car fleet of 1 billion 60 kWh EVs with NMC622 LIBs would require 11 million tons of cobalt, more than the estimated 7 million tons of global cobalt resources (USGS 2020).

In addition to the supply risks, 15-20% of the extracted cobalt in the DRC is mined artisanal with adverse environmental, human health and social impacts (Banza Lubaba Nkulu et al. 2018).

2.2.9 Manganese

Manganese provides structural stability to the LIB cathode (see subchapter 2.1.2) and is a cheap and abundant commodity (Figure 2.2.9). Large mining operations are located in South Africa (5,5 million tons production in 2019), Gabon (2,4 million tons) and Australia (3,2 million tons) (USGS 2020). European production is marginal, but several mining sites are located in Bulgaria, Romania and Hungary (European Commission 2017b). Thus, supply risk for the EU is at a medium level. The CO_2 emissions caused by manganese production are high, due to a complex extraction and refining process.



* Median for the year 2019. Commodity: Electrolytic manganese metal, Shanghai metal markets (SMM).
** Median of PEFCR and GREET values.. PEFCR: Manganese production, global; GREET: manganese ore and manganese.

Figure 2.2.9 Economic, political and ecological assessment of manganese per kg of raw material, plotted against the maximum value out of all 8 materials under consideration.

Own calculation based on: (DERA 2020), (Eynard et al. 2020a)(European Commission 2017a), (GreenDelta GmbH 2020)

2.2.10 Material comparison

The analysis of economics, political relevance, and environmental impact for the LIB raw materials[9] showed large differences between the materials. The following graphs summarize the results and put them into context. The political relevance (EU supply risk) is plotted as a bar chart on the right side of the graph, while the environmental impact (in kg CO_2-eq.) and the raw material price (in €) are shown as boxplot diagrams. The boxplot diagram for the raw material cost represents the material price

[9] The analyses focused on the metals and graphite. Excluded are plastics, electronics, carbon-based electrolyte components, and binders.

variations for all months of the year 2019. The boxplot diagram for the ecological footprint represents data from both the PEFCR database and the GREET tool.

Figure 2.2.10 shows the ecological footprint and the material cost per kg of raw material, whereas Figure 2.2.11 shows the normalized results when considering the amounts of material that are used per kWh of NMC622.

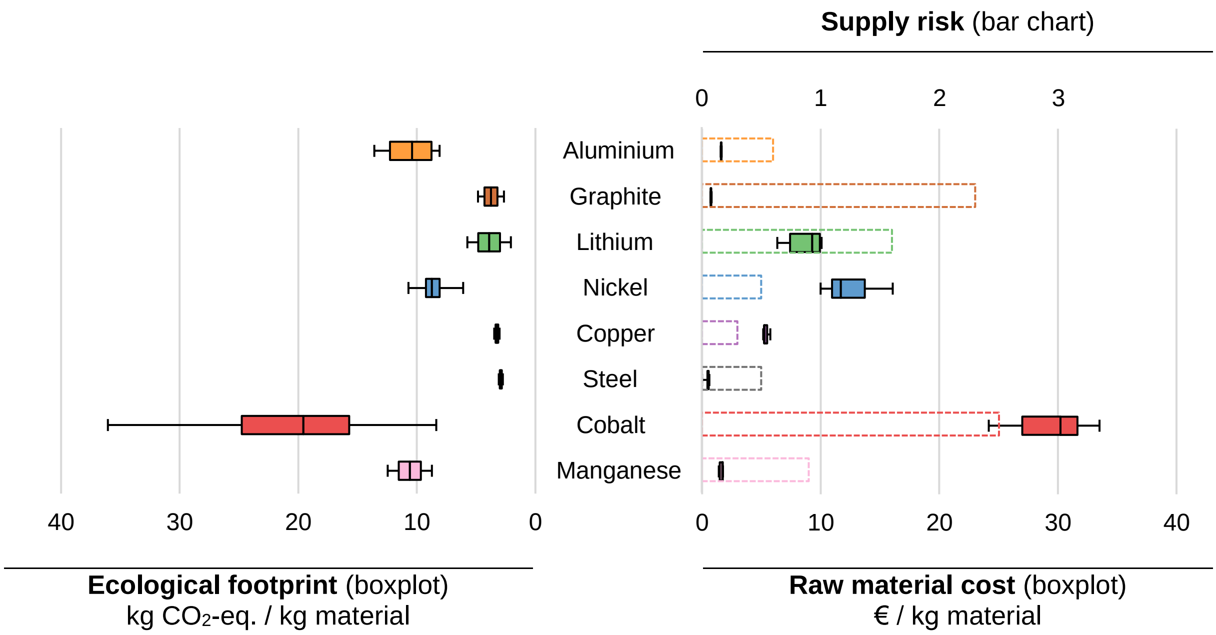


Figure 2.2.10 Economic, political, and ecological assessment per kg of raw material.

When just comparing the materials without considering the quantities inside LIBs (Figure 2.2.10), cobalt stands out as by far the most critical element inside the battery. It is the most expensive commodity and shows large price fluctuations over time, making it harder to make long-term business decisions both in the field of production and recycling. Furthermore, its ecological footprint is the largest and the supply risk for the EU is highest, due to a concentration of resources in just a few countries, mainly in the DRC. Correspondingly, battery producers are trying to reduce cobalt contents inside the battery to a minimum (see subchapter 2.1). It should be noted that the values for the ecological impact of cobalt deviate strongly between sources which creates uncertainty about their accuracy. Values lower than the mean value of aluminium, manganese and nickel are part of the range. For the raw material costs of batteries, besides cobalt, nickel, lithium and copper show the highest market prices. While graphite shows a low cost and low ecological footprint, its supply risk is second highest.

When considering the amounts of each material within 1 kWh of a NMC622 battery system (Figure 2.2.11), the situation changes. Aluminium becomes the material which produces the largest CO_2 emissions and furthermore nickel and graphite exceed cobalt when considering the mean values. In the economic dimension, nickel causes the largest raw material acquisition costs, followed by both cobalt and lithium, which has important implications on the recycling process. Even though natural graphite is defined as a critical raw material by the EU, due to its very low market price and substitutability with artificial graphite it represents a low risk factor for the battery industry.

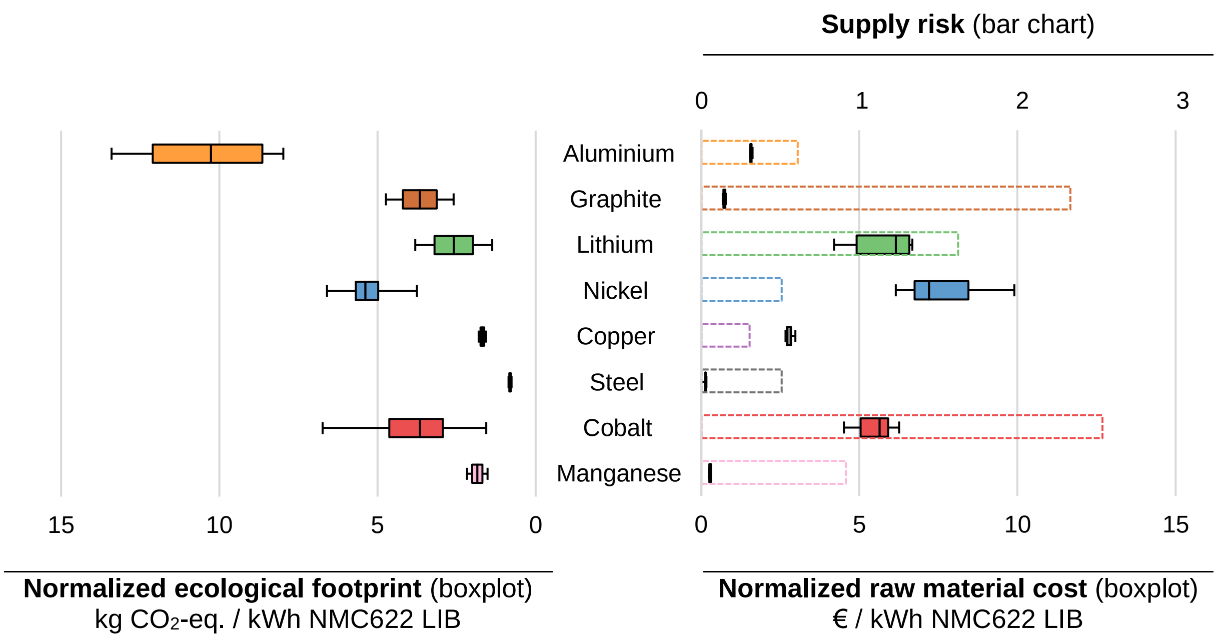


Figure 2.2.11 Normalized economic, political, and ecological assessment per kWh of NMC622 LIB.

The emissions caused by metal extraction and the market prices are of special interest when evaluating the economics and sustainability of EOL alternatives such as recycling and repurposing.

2.3 Lithium-ion battery manufacturing

The production process of LIBs can be divided into electrode manufacturing, cell assembly, formation cycles, module assembly, pack assembly, and final testing (Hettesheimer 2017). LIB production is an energy intensive process and as such can cause high GHG emissions if the energy is supplied by fossil fuels. Majority of production is located in Asia, with production of LIB electrode materials concentrated in China (48%) and Japan (29%) and production of LIB cells in China (66%) and South Korea (13%) (Blagoeva et al. 2019).

The following subchapters will discuss the environmental and economic impacts of battery production.

2.3.1 Economics of manufacturing

The calculation of production costs was based on the Battery Performance and Cost model (BatPaC) developed by Argonne National Laboratory which is sponsored by the US Department of Energy (Nelson et al. 2019).

The costs of battery production were modelled for a facility producing 60 kWh packs with NMC622 battery cells and a yearly production of 10 GWh and 20 GWh, respectively. The BatPaC default values for the numerous cost factors, including processed input materials and production costs were adopted and converted into euros (exchange rate EUR/USD of 0,89).

As seen in Figure 2.3.1, half of the costs are associated with material acquisition, of which the cathode active materials make up the largest share, followed by the anode materials. Purchased items such as cell and module hardware account for a quarter of total pack costs, while labor in a large-scale production facility accounts for only 2% of costs. Out of labor, electrode processing (23%) and cell assembly (29%) require the most working hours and correspondingly account for the highest costs.

Costs to produce one pack made up of 240 NMC622 cells is calculated to 6.596 € or 110 €/kWh when produced in a 10 GWh production plant and 6.927 € or 103 €/kWh when produced in a 20 GWh facility. The lower costs in the larger facility can be explained through economies of scale with lower labor hours per battery and a reduction of other costs such as administration and research.

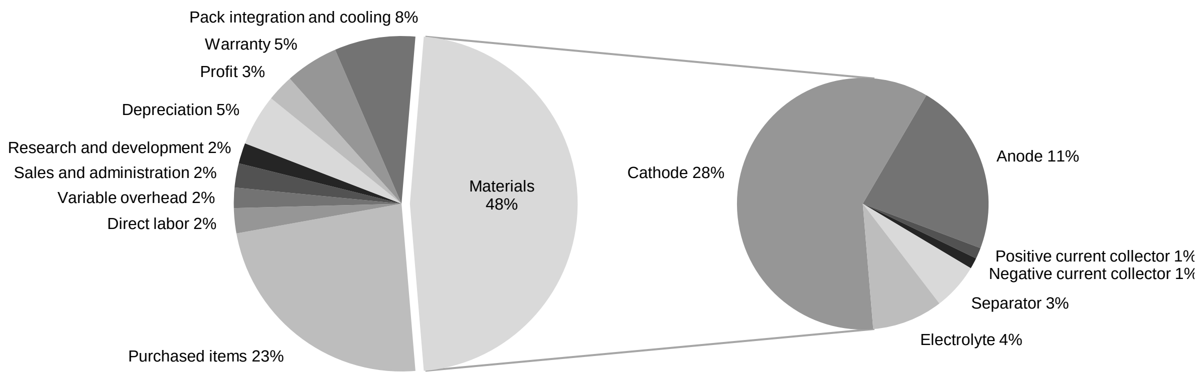


Figure 2.3.1 Cost distribution per pack for a 10 GWh NMC622 LIB production facility producing 60 kWh packs.

Own calculation based on: (Nelson et al. 2019)

2.3.2 Environmental impact of manufacturing process

Environmental impacts of LIB manufacturing are in part caused by using toxic solvents such as NMP in the cathode slurry mix, but mainly by the high energy consumption of electrode production and cell assembly. The energy consumption for the production of a LMO battery was found to be primarily influenced by the need to condition the dry room (43% of energy consumption) and the drying process during the electrode preparation (38%) (Yuan et al. 2017). Other process steps like stacking the electrodes or the sealing accounted for only marginal shares.

In this thesis the environmental impact of battery production will be approximated by calculating the global warming impact of the energy consumption during manufacturing. Studies on the environmental impacts of battery production show widespread results, see (Peters and Weil 2018). To generate reliable data points, the GREET model developed by Argonne National Laboratory was used (Wang 2019) and later compared to literature values. The model simulates energy use and emissions of different vehicle and fuel combinations and includes data on LIB production. The Microsoft Excel based model is transparent by showing all variables and furthermore allows the user to specify different input parameters of the production process and thus tailor the analysis to own needs.

Input material composition was adjusted to the NMC622 LIB material composition, and emissions of electricity production were changed to the values proposed in the EU PEFCR study for High Specific Energy Rechargeable Batteries for Mobile Applications, using an average European electricity grid mix.

Energy consumption for LIB cell production and battery pack assembly was calculated to 214,342 MJ per kWh of LIB pack which corresponds to ranges found in the literature, i.e. (Davidsson Kurland 2020) or (Erik Emilsson 2019).
With an average European electricity grid mix that causes 0,424 kg CO_2eq./kWh (GreenDelta GmbH 2020), emissions of LIB production are estimated at 25,251 kg CO_2eq./kWh.

2.4 Legislative framework for lithium-ion batteries in the EU

The EU set out its strategic action plan on batteries in 2018 to create a competitive and sustainable battery value chain in Europe (European Commission 2020). The European Battery Alliance (EBA), launched in 2017, became an integral part of the action plan to connect stakeholders along the entire value chain. A variety of different EU regulations govern the battery sector. Four key legislations will be presented in more detail to point out their impact on the LIB sector.

2.4.1 European Battery Directive 2006/66/EC

The European Battery Directive (on batteries and accumulators and waste batteries and accumulators) was adopted in 2006 and repealed Directive 91/157/EEC from 1991 (on batteries and accumulators containing certain dangerous substances). It forms the main legislation on batteries in the EU and aims at minimizing negative impacts of batteries on the environment and ensure the smooth functioning of the market. The legislation is not tailored to LIBs, which are not mentioned directly and fall under the category of “other waste batteries” in the category of “industrial battery or accumulator”.

The Battery Directive introduced the producer responsibility, by which whoever places batteries on the market is responsible to finance collecting, treating, and recycling once they reach the EOL. At the same time, the Directive prohibits the disposal of industrial batteries in landfills or by incineration (Article 14). Furthermore, battery collection rates for EU member states were required to reach 45% by 2016 (Article 10), and recycling processes of batteries need to achieve recycling efficiencies of 50% by average weight (higher only for for lead-acid (65%) and for nickel-cadmium batteries (75%)), whereas it is not prescribed which material should be recycled.

The Battery Directive is currently under revision, with an evaluation report published in 2019 (European Commission 2019a). The evaluation study stated that out of 28 member states, 14 countries met the 2016 collection target (2 countries did not report), and 22 the recycling target (6 countries did not report). Overall, the evaluation report acknowledged the positive environmental impacts and a contribution to a well-functioning EU battery market, whereas several areas were detected for improvements. For example, there is no clear legal framework for second life of batteries, and recycling efficiencies are not specified in detail and thus do not promote the recycling of valuable materials to secure a European supply of secondary raw materials (European Commission 2019a).

2.4.2 European Ecodesign Directive 2009/125/EC

The European Ecodesign Directive provides EU-wide rules for improving the environmental performance of products and sets out minimum mandatory requirements for the energy efficiency of these products. A preparatory study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage was published by the European Commission (EC) in 2019 with the target to establish sustainability requirements for batteries. The preparatory study analyses various aspects of the battery sector with a total of 7 sub-reports following the EU Methodology for Ecodesign of Energy-related products. The study includes:

- task 1: product scope with an overview of definitions and relevant legislation,
- task 2: battery and EV market analysis,
- task 3: analysis of battery user behavior,
- task 4: study of battery chemistry and production technology,
- task 5: environmental and economic impact assessment for different type of EVs and energy storage systems (ESS),
- task 6: discussion of possible design options such as reuse to reduce environmental impact,
- task 7: policy scenario analysis with estimated environmental and economic impacts.

2.4.3 End of Life of Vehicles Directive 2000/53/EC

Directive 2000/53/EC on end-of life vehicles (ELV) was introduced in 2000 to improve dismantling and recycling of EOL vehicles. It encourages vehicle manufacturers to reduce the use of hazardous substances and promotes reuse and recovery of components. From 2015, reuse and recycling rates of 85% by average weight per vehicle and year are required (Article 7). Hazardous materials and components of EOL vehicles must be removed and treated in a selective way (Article 6). Furthermore, adequate collection systems must be installed (Article 5), and member states are required to perform transparent reporting on the implementation of the Directive (Article 9). The ELV Directive will be reviewed until 31 December 2020.

2.4.4 European agreement concerning international carriage of dangerous goods by road

The European agreement concerning the international Carriage of Dangerous Goods by Road (ADR) was developed under auspices of the United Nations Economic Commission for Europe and entered into force in 1968. Since then, regular amendments kept the regulation up to date. In the 2019 version of the ADR (ECE/TRANS/275), LIBs fall under the class of “miscellaneous dangerous substances and articles” and need to pass various tests before being eligible for road transport. Testing criteria is defined in section 38.3 of the UN Manual of Tests and Criteria (ST/SG/AC.10/11/Rev.7). Furthermore, production of LIBs needs to be under a recorded and traceable quality management program that is specified with different requirements. Damaged or defective LIBs are listed separately, need to be marked as “DAMAGED/DEFECTIVE LITHIUM-ION BATTERIES”, and require special transport conditions following UN regulations (part 376 of the ADR). The ADR imposes strict regulations on cross-border transport of LIBs in the EU and thus impacts the entire EOL treatment.

2.4.5 Other relevant legislation

Several other regulations that impact the battery industry are listed hereafter.

- Waste of Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU
- Directive 2011/65/EU on the Restrictions of Hazardous Substance (RoHS)
- Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
- Regulation (EC) No 765/2008 on CE marking
- The battery capacity labelling regulation 1103/2010
- The UNECE R100 vehicle regulation
- The Energy Labelling Framework Regulations (ELR) (2017/1369)
- The Framework Directive on type-approval for motor vehicles
- Directive 2014/35/EU on harmonization of laws on Low Voltage equipment (LVD)
- Regulation (EU) No 2019/631 on CO_2 emission performance standards
- Car labelling Directive 1999/94/EC
- EU raw material initiative with the EU list of critical raw materials
- European agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (AND)
- Regulation concerning the International Carriage of Dangerous Goods by Rail (RID)
- International Maritime Code for Dangerous Goods (IMDG)
- International Air Transport Association Dangerous Goods Regulations (IATA DGR)

3 End-of-life alternatives for lithium-ion batteries from passenger car electric vehicles

After raw material mining and refining, the battery materials are used to manufacture LIBs which in turn can power EVs. Over the use phase, capacity fades and customer driving range demand can at some point no longer be met. The United States Advanced Battery Consortium (USABC) defined the EOL of EV batteries when the battery capacity reaches 80% of its nominal capacity (USABC 1996).

When entering their EOL, LIBs are collected, and different routes of treatment are possible. In the past, recycling of batteries was the dominant option. According to the EU Battery Directive (subchapter 2.4), EOL LIBs are required to fulfill recycling efficiencies of 50% by weight. However, with 80% remaining capacity, EOL batteries are still capable of functioning in a second life application in which energy density is less critical, such as stationary storage. Therefore, instead of going directly to recycling, EOL batteries can enter a second life first and thus delay the necessity of recycling by several years. Batteries can either be repaired and reused as an EV battery (remanufacturing) or refurbished and used for a different application such as stationary energy storage (repurposing). After the second life batteries will enter the recycling process to recover the materials. Different recycling technologies are implemented on an industrial scale. After the recycling stage, the recovered materials can be used again in the battery production process, generating a circular material flow (Figure 2.4.1).

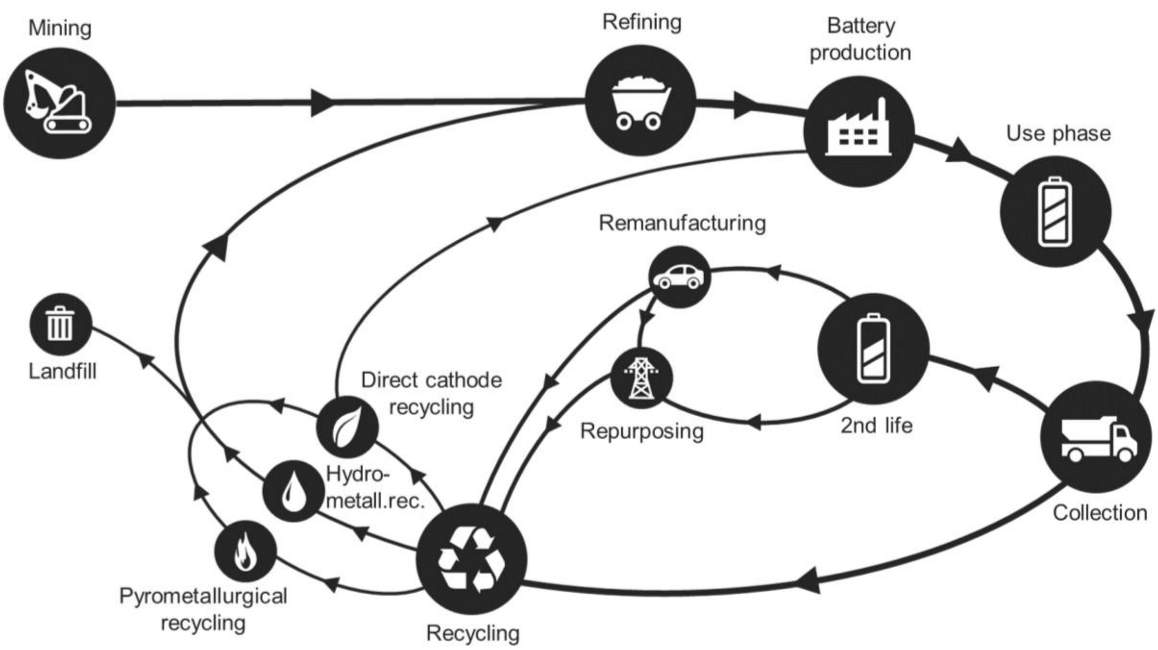


Figure 2.4.1 Life cycle of EV LIBs.

Inspired by: (Gaines 2019)

The following subchapters presents the details of second battery life and battery recycling. Subchapter 3.1 analyses different strategies of reusing and repurposing LIBs, while subchapter 3.2 gives a technical and environmental assessment of today's most common recycling technologies (hydrometallurgy and pyrometallurgy) and furthermore discusses the new approach of direct cathode recycling.

3.1 Second battery life

When testing of EOL batteries reveals that the majority of battery cells is still functioning properly, the few damaged cells can be replaced, and the battery system can be reused in EVs (Foster et al. 2014). Such process is called “remanufacturing”. Furthermore, once batteries fall under the performance requirement for usage in EVs, they might still hold sufficient energy for other applications in which weight and volume are less critical factors, such as stationary storage systems (Chen et al. 2019). This “repurposing” includes disassembly to module or cell level, testing of the battery, replacing of defective cells and reconfiguring the battery system to its new purpose (Fan et al. 2020). If managed properly, such repurposed batteries can last for another 10 years or more (Neubauer et al. 2015b).

3.1.1 Applications

Examples of potential second life battery applications made from repurposed LIBs are shown in Figure 3.1.1. On a larger scale and in collaboration with utilities, second life batteries can provide services to the electricity grid by offering a flexible energy storage with a short response time (Lacey et al. 2013). For example, the battery storage system can stabilize the grid frequency or serve as an immediate reserve or backup for unexpected drops in electricity production. Furthermore, the storage can be used to buffer intermittent renewable energy production and supply the energy to the grid when demand is highest (Hossain et al. 2019). The second life storage unit can also support generation side asset management, such as compensating fossil power production during periods of plant maintenance or securing the black start of power plants after a blackout (Hossain et al. 2019). Industrial consumers can use battery storage systems to reduce energy demand from the grid in peak load periods or utilize the system for energy arbitrage (Hossain et al. 2019). For the mobility sector, battery storage systems can support EV charging stations that require high energy in a short amount of time for rapid charging (Gohla-Neudecker et al. 2017). If testing reveals no safety concerns, EOL batteries can furthermore be reused to power lower range EVs (Foster et al. 2014). Other mobile applications are seen in the maritime sector where batteries can power electric boats, for which weight and volume are less critical compared to transport on the road. This was most recently demonstrated in a collaboration of Renault and Seine Alliance and their all electric vessel “Black Swan” (Groupe Renault 2019). Lastly, smaller storage systems can be used as home storage systems for private consumers, to e.g. store electricity from solar PV and increase energy self-sufficiency (Assunção et al. 2016).

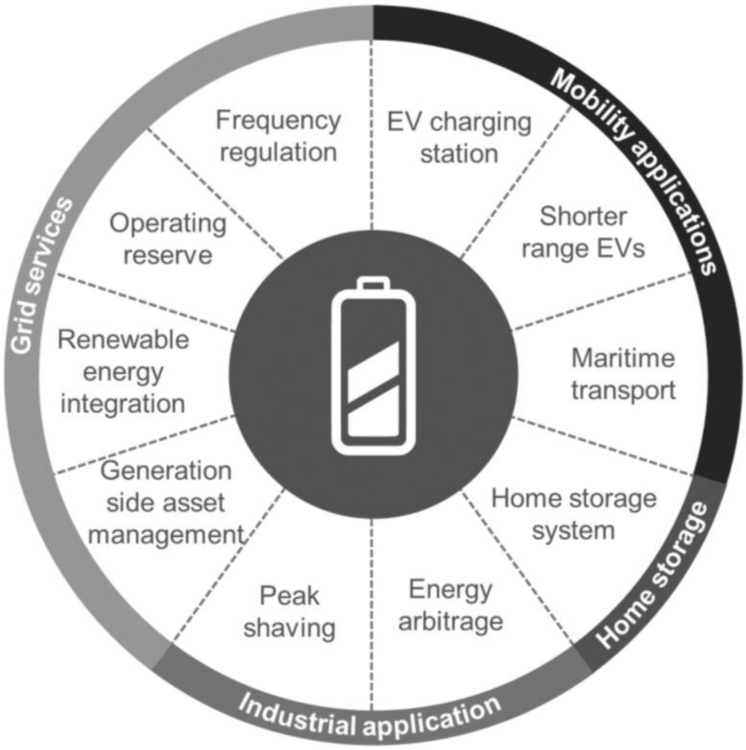


Figure 3.1.1 Overview of potential second life battery applications made from repurposed LIBs.
Inspired by: (Reid and Julve 2016)

The various potential applications require the collaboration of different stakeholders, and different business models arise. Once batteries reach their EOL, different entities can provide the second life service. The automakers are familiar with the battery design and know most about the battery usage profile during the lifetime through BMS data. Utilities and energy service providers have technical knowledge on the possible applications and experience with grid services but lack state of health information of the EV batteries. Private households and industrial players have interest in cheap storage solutions but lack the technical knowledge. Based on the different stakeholder types, several business models can emerge. In a supplier-customer relationship, the owner of the EOL batteries, or the original equipment manufacturer (OEM), sells the batteries to the provider of the second life solution. In a collaboration, the owner of the battery and the service provider can form a joint venture to share responsibility and revenues. Lastly, the OEM can internalize the repurposing into its own business (Pistoia and Liaw 2018).

3.1.2 Projects with repurposed batteries

The utilization of second life batteries has gained interest from academia, political actors, and private entities. From 2015 to 2018, an EU project called Energy Local Storage Advanced System (ELSA) set out to develop a stationary storage system based on second life EV batteries without previous dismantling of the individual battery packs (European Commission 2019b). Six pilot sites in Germany, France, Italy and the UK were equipped with Renault Kangoo Z.E. and Nissan Leaf second life batteries. The batteries were installed in industrial and academic buildings for ancillary services with integration of solar PV.

The project developed a fully operational converter system to regulate the second life EV batteries, and the running pilot systems indicated to be economically viable and able to generate environmental benefits. However, the pilot setups consisted of a small number of EOL battery packs, and a scale up of the ELSA battery energy storage system still needs to prove its benefits and long term stability (Diekerhof et al. 2018).

On the industrial scale, several collaborations between utilities, energy storage technology provider and car makers exist in the field of second life batteries. A starting advantage is held by those automakers who supplied the early successful EV models such as the Nissan Leaf (released in 2010) or the Renault Kangoo Z.E. (released in 2011), for which large quantities of batteries are already retiring. As an overview, Table 3.1.1 shows several European industrial second life battery projects, which are explained in more detail in the following paragraphs.

Table 3.1.1 Industrial second life battery projects in Europe.

Year	Storage capacity	Partners	Location	Application
2015	720 kWh/ each	Connected Energy, Renault	Several European countries	RES integration, frequency regulation, virtual power plant, EV charging stations
2016	13 MWh	GETEC, The Mobility House, Daimler	Lünen, Germany	Frequency regulation
2016	2,8 MWh	Vattenfall, Bosch, BMW	Hamburg, Germany	Frequency regulation
2017	4-8 kWh/ each	Powervault, Renault	Greenwich, UK	Home storage systems
2018	2,8 MWh	Eaton, The Mobility House, BAM, Nissan	Amsterdam, Netherlands	RES integration, frequency regulation, backup, peak shaving
2019	1,9 MWh	The Mobility House, Audi	Berlin, Germany	RES integration, frequency regulation, peak shaving, EV charging station
2019	60 MWh	The Mobility House, Renault	Douai, France	Frequency regulation, peak shaving

The energy storage provider Connected Energy won the British Renewable Energy Award in the category of innovation in 2015 for integrating EOL batteries from Renault Kangoo Z.E. vehicles into their 720 kWh energy storage system E-STOR. The system has now been implemented throughout Europe for various purposes such as EV charging stations, solar PV integration, grid frequency response, or as part of a virtual power plant (Groupe Renault 2020) (Connected Energy 2020).

In 2016, a joint venture of energy service provider GETEC, energy storage company The Mobility House, and automaker Daimler, developed the at that time largest second-life battery storage system with a capacity of 13 MWh in Lünen, Germany. The solution used 1.000 retired batteries from the Smart Fortwo electric drive to provide ancillary services such as frequency regulation to the grid (Daimler 2016). Two years later, the same entities joined forces again to build another storage unit of 10 MWh capacity, this time instead of using second life batteries, building a living spare parts warehouse comprised of Smart EV battery packs that are stored to replace defective packs in running EVs. While the batteries are stored, they support the local grid as a flexible storage unit (The Mobility House 2018b).

Another collaboration in the north of Germany was formed by technology provider Bosch, the utility Vattenfall, and automaker BMW. The stationary storage unit with a capacity of 2,8 MWh is made of EV batteries from more than 100 BMW i3, mainly from test vehicles whose batteries already reached their EOL in the automotive application. The system is operated by Vattenfall to provide frequency regulation to the grid (Vattenfall 2018).

The British energy storage company Powervault partnered with Renault in 2017 for a 1-year pilot project in which they provided 50 home storage systems to households in the UK. The storage uses second life batteries from Renault vehicles (Powervault 2017). Today, Powervault offers on its website its home storage system Powervault 3eco with a capacity ranging from 3,9 to 7,9 kWh, using second life LMO battery cells (Powervault 2020).

Since 2018, the football stadium from Ajax Amsterdam, the Johan Cruijff Arena, utilizes retired Nissan Leaf batteries to reduce the pressure on the grid during football matches. Furthermore, the system buffers the solar PV production of the building’s rooftop system and offers frequency regulation to the grid. The project was realized in a partnership of energy technology provider Eaton, the Mobility House and automaker Nissan. About 140 EOL Nissan Leaf batteries are coupled to provide a storage capacity of 2,8 MWh (The Mobility House 2018a).

The German automaker Audi started a pilot project on the EUREF Campus in Berlin in 2019. The stationary storage system has a capacity of 1,9 MWh and uses EOL batteries mainly from Audi test vehicles to offer frequency regulation to the grid (Audi 2019).

A similar service is provided by a project initiated by Demeter, The Mobility House, and Renault, aiming to develop the biggest EOL battery stationary storage system in Europe to offer energy services such as peak shaving to the grid. The system will be implemented in sites located in France and Germany to offer a total of 60 MWh storage capacity, utilizing 2.000 second life battery packs (The Mobility House 2019) (Electrive 2018).

The trend is clear and other big players are trying to join the repurposing market. Volkswagen announced to start producing its own EV charging stations “power bank for the e-car” in 2020, and enabling the integrating of second life batteries into their solution (Volkswagen 2018).

Research is also investigating novel applications of second life batteries. Seine Alliance, a French maritime company, unveiled in late 2019 its all electric boat, the Black Swan, fueled by second life Renault batteries (Groupe Renault 2019).

Such initiatives show the great market dynamic that can be seen in the field of EOL EV batteries. In addition to the pilot projects, several scientific publications assessed the economic and environmental impacts of a second battery life.

3.1.3 Ecological assessment

The ecological assessment of second life batteries is case specific due to the individuality of the reused batteries such as the state of health (SOH). Furthermore, different potential second life applications vary in their load profiles, which results in varying second lifetimes, and consequently different ecological impacts (Bobba et al. 2018a).

As seen in Figure 3.1.2, the first step of EOL treatment is the collection of the batteries and the transport to the refurbishment factory. In a study conducted for the European Commission, (Bobba et al. 2018a) assumed an average transport distance of 100 km to collect the batteries inside Europe and bring them to the place where the refurbishment occurs.

In the refurbishment factory, testing of modules reveals the cells SOH. Depending on the performance characteristics, individual cells might have to be removed to allow for a balanced system consisting of cells with similar capacities. Historical studies on the environmental impact of repurposing batteries allocated a high energy demand to the testing of the battery modules. (Richa 2016) estimated a test consisting of 4 charge/discharge cycles and requiring 10,69 kWh per kWh of tested battery. In a more recent study, (Bobba et al. 2018a) estimated an electricity consumption for one charge/discharge cycle of 8,72 kWh for their second life battery with an original capacity of 11,4 kWh. However, recent technological developments show drastic improvements in battery testing. In a collaboration with Nissan, researchers from the University of Warwick in the UK have developed an EOL battery grading process based on electrochemical impedance spectroscopy that can assess the SOH of modules in as little as 3 minutes, a process that formerly required up to 3 hours (University of Warwick 2020). The technology was commercialized by the electronics company Ametek with a product launch in 2020 (Clements and Ruf 2020). With such instant battery grading technology, costs, and energy demand of the testing procedure can be expected to drop significantly.

Finally, to equip the system for its new purpose, several modifications are made, such as adding a new BMS and making adjustments to the casing (Richa 2016). The casing system requires a battery retention system to fix the batteries within a battery tray made of steel, equipped with elements of the cooling system (Ellingsen et al. 2014). Figure 3.1.2 shows the steps in the battery repurposing process.

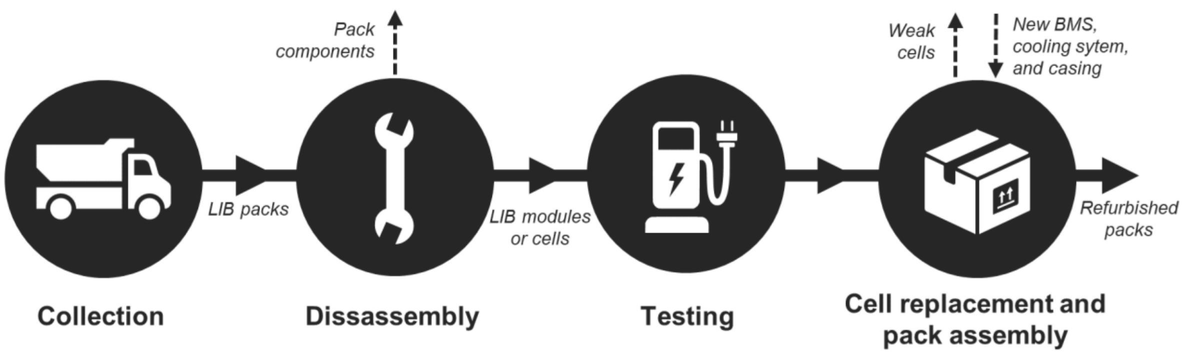


Figure 3.1.2 Process steps during battery repurposing.

The life cycle assessment of (Bobba et al. 2018b), as part of the Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB) for the European Commission, showed that the

largest share of GHG emissions during the repurposing is caused by the use of new materials, whose extraction and processing causes large emissions. Largest impacts were caused by the battery tray and the battery retention system.
The electricity consumption for testing (1 full discharge cycle), as well as the transport of the batteries showed a negligible impact on production of GHGs in their study. Assuming a further decrease of energy demand for testing of batteries due to the technological improvements of testing methods, an approximation of the environmental impact of the repurposing impact can be made by adding up the impact of additional materials and the transport.

In the case of the NMC622 LIB defined in subchapter 2.1, the emissions allocated to BMS, thermal management system and casing materials on pack level can be calculated to 15,145 kg CO_2eq./kWh (see Annex Table A.7). The emissions produced by transport of goods with trucks can be calculated based on the PEFCR database. A Euro 4 lorry transport (>32 tonnes) fueled by diesel will produce 0,053 kg/1000 kgkm and thus 0,028 kg CO_2 to transport 1 kWh of a NMC622 LIB pack (5,238 kg/kWh) for 100 km (GreenDelta GmbH 2020). Thus, emissions caused by inner European transport are negligibly small compared to emissions caused by the new materials which are required.

3.1.4 Economical assessment

While the environmental benefits of reusing EOL batteries seem to be evident due to the reduction of newly produced batteries, the economic feasibility must be secured to convince industrial players to implement the technology on a broader scale. Many studies already indicate economic benefits, while uncertainty exists in terms of the regulatory framework and the absence of long-term studies on the behavior and safety of second life batteries over their second lifetime (Ahmadi et al. 2014).

To be economically feasible, repurposed batteries must have lower costs than first life batteries with comparable specifications. (Neubauer et al. 2015a) set up an analysis to calculate the costs for repurposing. Their model included costs for transport of batteries, capital and labor costs inside the refurbishment factory and other costs such as insurances and warranties. For a large-scale facility with a throughput of 600 MWh of batteries per year, they calculated a repurposing cost between 22 and 44 €/kWh (convert to Euro with exchange rate of 0,89 EUR/USD). They assumed that the original owner of the EOL battery will be paid to provide the batteries, with selling prices ranging from 17 to 117 €/kWh dependent on battery health. A variety of scenarios with varying costs of repurposing and battery selling prices were studied. For all scenarios under consideration, the repurposed battery selling price was estimated to be significantly cheaper than an equivalent new battery. The US National Renewable Energy Laboratory (NREL) provided the underlying Excel based calculation sheet that allows to retrace the simulation set up and adjust individual parameters (National Renewable Energy Laboratory 2020). The default settings are set for an EOL module with 115 Wh/kg battery cells with 70% remaining capacity. Cell default rate is set to a very low 0,001%, and the purchase price of the EOL batteries is 39 €/kWh. With a facility throughput of 1 GWh/year, repurposing cost is calculated to 22 €/kWh.

While these calculations show clear benefits of using EOL batteries instead of new batteries, certain business risks are posed by the lack of clear regulations. The EU introduced the producer responsibility to oblige whoever places the batteries on the market to take care of their disposal after usage (European Commission 2006). However, the EU legislation currently does not specify the case of second life batteries, and batteries are classified as “waste” after their first life (Bobba et al. 2018a). While recycling is encouraged and minimum recycling rates are fixed, the European Battery Directive does not mention the reuse or repurposing of batteries (European Commission 2006). A lack of clear regulation hampers business decisions. Furthermore, the safety of repurposed batteries is a critical area. Fire and explosion are a cause of concern for LIBs, and there is still a lack of long-term studies to examine battery health over the second lifetime. Therefore, high security measures are needed to avoid accidents and prevent fire propagation (Fan et al. 2020).

Despite the drawbacks through the lack of regulation and safety concerns, the large number of pilot projects discussed in subchapter 3.1.2 indicates that industrial players are aware of potential economic benefits that second life applications promise.

3.2 Recycling of LIBs

To recover valuable materials and reduce the environmental impacts, batteries can be recycled after reaching their EOL. Waste LIBs in the EU need to achieve recycling efficiencies of 50% by average weight as defined in the Battery Directive (European Commission 2006), but companies are free to choose which materials to recycle and how. While lead-acid batteries achieve recycling rates of almost 100% (Blanpain et al. 2014) and processes are cost-efficient due to standardized designs and chemistries (Harper et al. 2019), LIBs face problems in a variety of domains. Battery packs consists of several modules and hundreds of cells, and cell geometries vary strongly between cylindrical, prismatic and pouch cells. Due to technological development, chemistries are constantly changing, and a variety of different cathode chemistries exist (Gaines 2014). While lead-acid batteries contain the highly toxic metal lead, materials in LIBs are less dangerous to human health. Nevertheless, they pose significant danger in handling due to the high energy content and the combustible electrolyte (Pistoia and Liaw 2018).

Interesting for the recycling process of LIBs are especially the battery cells and inside the cells the cathode, which holds the highest concentration of high value materials (such as cobalt, nickel and lithium). The rest of the batteries (module and pack casing, electronic elements, etc.) are mainly composed of materials for which traditional recycling routes already exist (such as aluminium, steel and plastics) (Pistoia and Liaw 2018). Current recycling processes are optimized to the recovery of cobalt and nickel (Ager-Wick Ellingsen and Hung 2018), but with changing chemistries and expected higher targets for EU recycling rates, the recovery of other fractions, especially lithium, is shifting into focus.
The predominant recycling processes to treat LIB cells are pyrometallurgy and hydrometallurgy, and both are used on an industrial scale (Chen et al. 2019). Direct cathode recycling is still in the research stage but promises a cheaper handling of batteries. In direct cathode recycling, instead of raw materials, battery grade cathodes are recovered and thus costs and environmental impact of the cathode production are avoided (Harper et al. 2019) (Ciez and Whitacre 2019).

The 3 different recycling routes for LIBs are visualized in Figure 3.2.1. The following subchapters provide further information into the recycling steps and the different technologies. Furthermore, the economic and ecological impact of recycling LIBs is assessed.

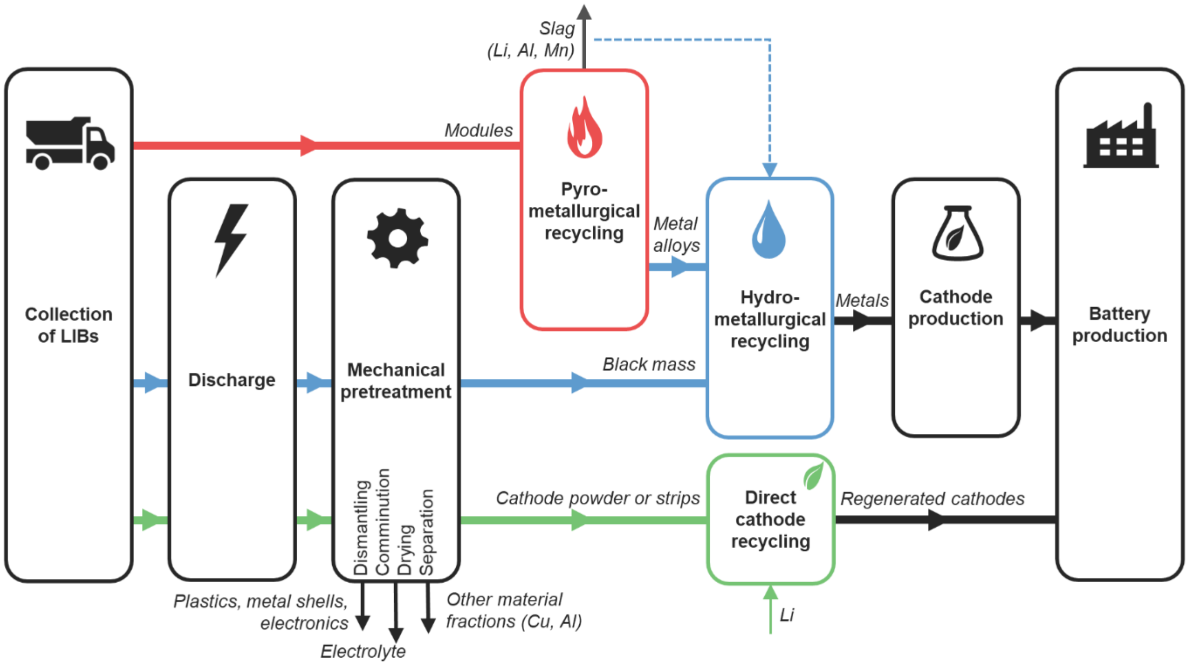


Figure 3.2.1 Different recycling routes for LIBs.
Inspired by: (Chen et al. 2019), (Hanisch et al. 2015), (Huang et al. 2018), (Harper et al. 2019).

3.2.1 Pretreatment

After collection and transport to the recycling facility, battery packs are tested and in the case of hydrometallurgical treatment and direct cathode recycling, they must be discharged and dismantled before entering further processing steps (Harper et al. 2019). While this adds additional processing steps and can increase costs, the discharge and dismantling process facilitates later separation steps and recovers the residual energy of the batteries, which can be used to power the later processing steps or can be fed into the grid (Harper et al. 2019). Furthermore, the discharge process reduces safety risks in subsequent handling (Pistoia and Liaw 2018). After the discharge process, battery packs are dismantled and sorted into material fractions.

Since recycling facilities receive battery packs from different OEMs, they have to cope with a variety of different cell designs and variations in cathode chemistries (Hanisch et al. 2015). Furthermore, in the EU there is no regulation on the labelling of the battery material composition, which leaves recyclers with uncertainty about the LIB type they are dealing with[10].

Therefore, an automation of the disassembly process is difficult and requires manual work (Harper et al. 2019). The process is further complicated by safety concerns in the handling of LIBs caused by electrical, fire and chemical hazards (Diekmann et al. 2017).

[10] The EU Battery Directive solely requires labelling of batteries with a symbol indicating “separate collection”, visualized as crossed-out wheeled bin. Batteries with high amounts of mercury, cadmium, or lead furthermore require a symbol indicating which heavy metals are used inside the battery (European Commission 2006).

The high electric energy inside the battery poses the danger of electric shocks (electrical hazard). Short circuits can lead to high temperatures and ignition of the carbonates in the electrolyte (fire hazard). Toxic gaseous reaction products can result from the decomposition of the electrolyte (chemical hazard).

To achieve faster, cheaper, and safer disassembly, several research projects investigate the semi or full automation of the disassembly process using robots. For example, (Wegener et al. 2015) proposed a hybrid human-robot-working-space to improve the disassembly process of large traction batteries as part of the LithoRec project on LIB recycling in Germany. In the sample set-up for an Audi Q5 HEV, the robot executes simple and repetitive work steps, while the human worker performs the more complex tasks. However, such automation approaches are still in the pilot stages (Harper et al. 2019).

Final part of the mechanical pretreatment is comminution and sorting (which are a prerequisite for the hydrometallurgical treatment, but not necessary for the pyrometallurgical treatment (Eduljee and Harrison 2019)). LIBs are commonly shredded in an inert atmosphere to avoid fire or explosion. An example of such process is seen in the Duesenfeld recycling plant in Germany, where shredding occurs in a nitrogen atmosphere (Duesenfeld 2020a). The French company Recupyl filed a patent for recycling of LIBs which includes a step of crushing the batteries under a mix of argon gas and CO_2 (Foudraz and Farouk 2007).

The comminution is followed by a drying process and different separation steps (for example based on physical properties such as grain size or magnetism) to presort the shredded batteries into distinct material fractions that are suited for further processing (Wang et al. 2016).

3.2.2 Pyrometallurgy

In a pyrometallurgical recycling treatment, LIBs are fed into a high temperature furnace together with a slag-forming agent (limestone, sand) to melt the batteries (Dunn et al. 2014), and without the necessity for pre-treatment such as discharge, comminution and separation (Chen et al. 2019).

During the process, organic compounds in the battery (plastics, electrolyte solvents and graphite) are burned and serve as a carbon source for the combustion (Gaines et al. 2010). The electrolyte evaporates, and the process yields a metal alloy containing the metals nickel, cobalt, and copper (Hanisch et al. 2015). The alloy can then be solubilized by using a hydrometallurgical process with leaching and purification with solvent extraction and precipitation to generate metal fractions which can be used for the manufacturing of new cathodes (Xiaxiao et al. 2018).

Lithium, aluminium and manganese remain in the slag of the pyrometallurgical treatment, which can be used as a construction material (Hanisch et al. 2015). However, with the continuous decrease of the high value material cobalt in LIB cathode chemistries, recyclers must look at other materials to make recycling profitable, and lithium recovery from the slag is shifting into focus.
Research projects on economically extracting lithium from the slag are executed around the world, using techniques such as chlorination roasting (Dang et al. 2018) or vacuum pyrolysis (Xiao et al. 2017).

The large advantage of the pyrometallurgical treatment of LIBs is the simplicity of the process. It avoids time-consuming testing to identify the chemistry mix or presorting of the batteries. Instead, batteries can be fed into the furnace without sorting or size reduction (Gaines et al. 2018b). On the downside, the process is energy intensive and produces high amounts of GHGs (Ciez and Whitacre 2019). Furthermore, organic materials are burned, and lithium ends up in the slag and requires complex treatment for recovery. Thus, overall material recovery rate for pyrometallurgical recycling is low.

One of the largest LIB recycling facilities in Europe is operated by Umicore with a capacity of over 7.000 tonnes per year (Eduljee and Harrison 2019), using a pyrometallurgical treatment. The plant gives an example of the process steps of a pyrometallurgical treatment. Packs are dismantled to module level before being fed into the furnace (Frank Treffer 2017). Due to the thermic gradient inside the furnace the batteries pass three types of treatment: preheating, pyrolysis, and smelting (Hanisch et al. 2015). The preheating in the upper part of the furnace to around 300°C evaporates the electrolyte and gaseous compounds. The released gases undergo an after-treatment outside the furnace, while the electrochemically inactivated cells enter the middle section of the furnace (temperatures of 700°C) where the pyrolysis of plastic compounds occurs. On the bottom of the furnace the temperature increases to above 1200°C and induces the smelting and reduction of the remaining materials, creating two distinct phases: a lithium rich slag and an alloy containing cobalt, copper, and nickel. The metal alloy is then processed hydrometallurgically to obtain nickel sulfate, cobalt chloride and copper sulfate (Hanisch et al. 2015). Recently, with the help of external partners, Umicore has furthermore demonstrated that lithium can be recovered from the slag (Chen et al. 2019).

3.2.3 Hydrometallurgy

Hydrometallurgical processes based on acid leaching have been gaining popularity due to their low energy consumption and high material recovery rates (Gaines 2018a). In contrast to pyrometallurgical treatment that avoids prior comminution, hydrometallurgy requires a pretreatment of the batteries, consisting of discharge, dismantling, shredding, and separation of the materials (see subchapter 3.2.1).

One of the outputs of the pretreatment process is the so-called black mass, a fine powder containing anode and cathode materials (Diekmann et al. 2017). This mix of materials can be treated hydrometallurgical to extract the individual metal components. During the leaching process, solutions are used to dissolve the blend, resulting in a mixture of different species in solution. With additional process steps such as precipitation or solvent extraction the individual materials can then be recovered (Gaines 2018a).

The leaching process requires the use of alkalis or acids such as sulfuric acid (H_2SO_4) and is influenced by the process parameters time and temperature (Larouche et al. 2020). Reducing agents such as hydrogen peroxide (H_2O_2) are added to improve the dissolution and optimize the process (Joulié et al. 2017).
In recent years, organic acids (such as citric acids) have gained popularity due to their biodegradability and weaker material corrosion, while still allowing for high leaching efficiencies (Larouche et al. 2020).

After leaching, the subsequent recovery (purification) can include electrochemical, precipitation or solvent extraction techniques (Zhu et al. 2012). Electrochemical extraction uses electrolysis to separate the fractions with high purity rates but also has a high energy consumption (Boxall et al. 2018). In a precipitation treatment, precipitation agents are used to separate the target metals. With low energy demand and low costs, precipitation is a suitable technique for extracting the materials, whereas the process can become complicated if the leaching solution is made up of too many different elements (Huang et al. 2018). With solvent extraction, an organic extractant is used to separate the solution into different phases and allow to recover individual materials. The process has a low energy demand, and good separation results, but extractants are expensive (Huang et al. 2018).

Overall, the advantage of hydrometallurgical recycling are the high recovery rates and quality of obtained materials and the low energy demand and environmental impact. Drawbacks come in the prerequisite of complicated and expensive pretreatment, as well as in water demand and wastewater treatment when strong acids are used, which can be avoided with the use of organic acids (Chen et al. 2019).

An example of a state-of-the-art hydrometallurgical recycling plant for LIBs is located in Germany and operated by Duesenfeld. Duesenfeld claims a cell material recycling rate of 91% with their mechanical and hydrometallurgical technology (Duesenfeld 2020b). As the first step in their process, batteries are discharged, and residual energy is used to fuel the following process steps. Packs and modules are then dismantled by hand to remove casings, BMS and cooling system. The remaining parts are shredded in an inert atmosphere, dried, and separated before the electrode materials and lithium salts enter the hydrometallurgical treatment, which recovers sulfates of cobalt, nickel, manganese, as well as lithium carbonate and graphite (Duesenfeld 2020b). Furthermore, the company developed flexible container solutions to perform the pretreatment steps decentralized wherever the waste batteries are located to avoid the legislative hurdles when transporting full batteries (Duesenfeld 2020c). In the case of decentralized pretreatment, only the hydrometallurgical treatment is then performed at the central Duesenfeld facility.

3.2.4 Direct cathode recycling

Non-destructive methods to directly regenerate the active cathode materials without the need of extensive additional processing are referred to as “direct recycling” (Larouche et al. 2020). To compensate for battery lifetime degradation in the form of lithium loss, lithium is replenished (relithiation) to recover the original battery properties (Shi et al. 2018).

Advantages of the process are the low carbon emissions and the quality of recovered materials which avoids the costs and effort of cathode production. However, the technology requires a high purity separation step since impurity can destroy the functionality of the recovered cathode. Furthermore, the process is inflexible to varying cell chemistries and has not been implemented in the industry (Chen et al. 2019).

Research on direct cathode recycling is led by Argonne National Laboratory in the US. The process proposed by researchers at Argonne includes a discharge and disassembly step similar to that in a hydrometallurgical treatment. After the disassembly, supercritical CO_2 is used to extract the electrolyte, after which it is safe to perform a size-reduction process on the now electrolyte-free cell. The pulverized materials are separated and the cathode fraction, after undergoing a relithiation step to compensate for degradation over the lifetime, can be reutilized as a cathode material (Dunn et al. 2014). Instead of pulverization and separation, in a research project by (Shi et al. 2018), entire cathode strips were extracted from pouch cells, requiring manual work but guaranteeing a high purity of materials.

3.2.5 Ecological assessment

(Ciez and Whitacre 2019) examined the GHG emissions of pyrometallurgical, hydrometallurgical, and direct cathode recycling processes for different LIB cell types, using a simulation of energy inputs and carbon emissions based on the GREET 2016.

Their pyrometallurgical process was based on a Umicore patent (Cheret and Santen 2007), in which the batteries are fed to the furnace together with limestone, sand and coke. The resulting metal alloy is leached to extract nickel, cobalt, and copper, while the slag is utilized as a construction material without further extraction of materials. A small fraction of the desired materials is lost in the slag, namely 7,2% of copper, 6,0% of cobalt, 1,0% of nickel (Ciez and Whitacre 2019).

The hydrometallurgical treatment used in the study included a mechanical pretreatment with discharge, disassembly, and shredding of the batteries, followed by separation steps. The cathode materials then undergo an acid leaching process to extract the individual metal components (Ciez and Whitacre 2019).

The simulated direct cathode recycling follows the procedure proposed by (Dunn et al. 2014). Like the hydrometallurgical treatment, the process starts with discharge and disassembly of the batteries. Thereafter, the electrolyte is extracted, and the component size reduced before cathode materials are separated (Ciez and Whitacre 2019). A relithiation step might be necessary before the cathode mix can be reused in a battery (Dunn et al. 2014). Materials which are not directly recovered in the hydrometallurgical and direct cathode recycling approach were assumed to be incinerated.

For NMC pouch LIB cells, the results of (Ciez and Whitacre 2019) analysis shows clear differences in GHG emissions between the different recycling technologies. While pyrometallurgical recycling treatment exceeded the emissions associated with virgin material production, both hydrometallurgical and direct cathode recycling showed environmental benefits. Thus, recycling with pyrometallurgy increased the overall lifetime emissions of the LIBs, while hydrometallurgy and even more direct cathode recycling reduced overall GHG emissions.

Due to the use of US electricity grid data by (Ciez and Whitacre 2019), the absolute numbers of the emissions associated with different recycling technologies will vary in the EU. Nevertheless, the relative comparison between the different technologies gives a good indication on expected environmental benefits. Direct cathode recycling promises the highest GHG savings but is still in a research phase. From the two industrially applied technologies, hydrometallurgy causes the smaller GHG impact and shows to be the environmentally preferable option.

An own calculation using the updated 2019 version of the GREET model (which includes life cycle calculations for battery recycling processes) was carried out, comparing 1) pyrometallurgical recycling, 2) hydrometallurgical recycling based on acid leaching and 3) direct cathode recycling, all on cell level (Dai and Winjobi O. 2019). The process steps are the one’s defined in the 2019 GREET version and resemble the one’s used in the simulation of (Ciez and Whitacre 2019) described above.

Results for total energy demand for the different recycling technologies are shown in Table 3.2.1. Furthermore, the corresponding emissions given an average European electricity grid mix of 0,424 kg CO_2/kWh (GreenDelta GmbH 2020) are specified[11].

Table 3.2.1 Energy demand and estimated emissions of different recycling technologies.

	Pyrometallurgy	**Hydrometallurgy**	**Direct cathode recycling**
Energy demand [MJ/kWh LIB cell]	66,375	29,133	23,061
Emissions [kg CO_2eq./kWh]	7,820	3,432	2,717

Own calculation based on: (GreenDelta GmbH 2020), (Wang 2019)

Pyrometallurgical treatment has by far the highest energy demand, double that of the hydrometallurgical treatment, caused by the high temperature smelting process. Direct cathode recycling requires the least amount of energy, and saves large emissions compared to the production of virgin cathode materials (Dunn et al. 2014). However, the depicted process only recovers the cathode materials. If other constituents are also recovered, this will impact emissions. The hydrometallurgical treatment has a low energy demand and seems favorable for industrial application. Many companies already apply a hydrometallurgical LIB recycling on an industrial scale, including Duesenfeld in Germany and Recupyl in France.

3.2.6 Economical assessment

Pyrometallurgical recycling requires high capital cost and only recovers a limited number of the valuable materials, while hydrometallurgical treatment and direct recycling require lower upfront investments and lead to high recovery rates but demand more and complex working steps and thus have higher operating costs (Harper et al. 2019) . With increased automation, especially in the pretreatment process, future costs could be decreased.

Due to the absence of industry data on costs of the recycling process, the potential revenues can be calculated to estimate a maximum tolerable cost of the recycling process. To be economically viable in the absence of governmental subsidies, total costs of recycling together with the purchasing price of the EOL batteries must be lower than the value of the recovered materials.

For a hydrometallurgical treatment that can recover all the cathode materials in a high enough quality to be sold at market price, the revenues can be estimated.

Exemplary this is done for the cathode materials. The active material of the base case NMC622 cathode is comprised of an equivalent of 0,584 kg/kWh lithium carbonate (the market commodity of lithium), 0,557 kg/kWh nickel, 0,174 kg/kWh manganese, and 0,186 kg/kWh cobalt. For a 215 Wh battery cell, this equals roughly 126 g lithium carbonate, 120 g nickel, 37 g manganese and 40 g cobalt, resulting in a revenue of 4,691 €/cell or 21,783 €/kWh (Table 3.2.2).

[11] Oversimplifying assumption that all energy is in the form of electricity.

Table 3.2.2 Theoretical revenues from recovering the active materials for the NMC622 LIB cathode materials.

	Lithium carbonate	**Nickel**	**Manganese**	**Cobalt**
Material weight per kWh of cell [kg/kWh]	0,584 *(0,11 Li)*	0,557	0,174	0,186
Median market price 2019 [€/kg]	10,439	15,022	2,192	37,308
Revenue per kWh of cell [€/kWh]	6,096	8,367	0,381	6,939

Own calculation based on: (DERA 2020)

As pointed out in subchapter 2.2.10, nickel shows the highest economical relevance for the profitability of the recycling process of a NMC622 LIB. Cobalt and lithium follow in economic importance, whereas the economic impact of cobalt is expected to decrease further with the development of lower cobalt content LIBs. Thus, the recovery of lithium is becoming more important, encouraging the use of hydrometallurgical recycling routes.

4 Methodology of scenario analysis

4.1 Introduction to scenario analysis

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).

In this work, the scenario analysis will follow a quantitative approach where various results are calculated for the period from 2020 to 2030. For each scenario dimension, three hypothetical future developments are defined: a rather optimistic one with regard to the goal of decarbonization, a rather pessimistic one and the reference case which is deemed as the most probable development.

The field of LIBs is an area of great uncertainty. Uncertainty exists about the transformation of road transport towards electrification or alternative fuels, about battery technologies, raw material supply, recycling and reusing of batteries.

By developing different narratives of the future and quantifying its implications, the results are not claiming to project the future, but rather to improve the discussion between the public, industrial players, and policy makers about the future of the LIB value chain in the EU.

The goal of the analysis 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. 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 4.1.1), while other factors were set constant. In addition to the four scenarios, a sensitivity analysis was carried out on the increase in BEV and PHEV sales to see how strong the overall results are influenced by this factor.

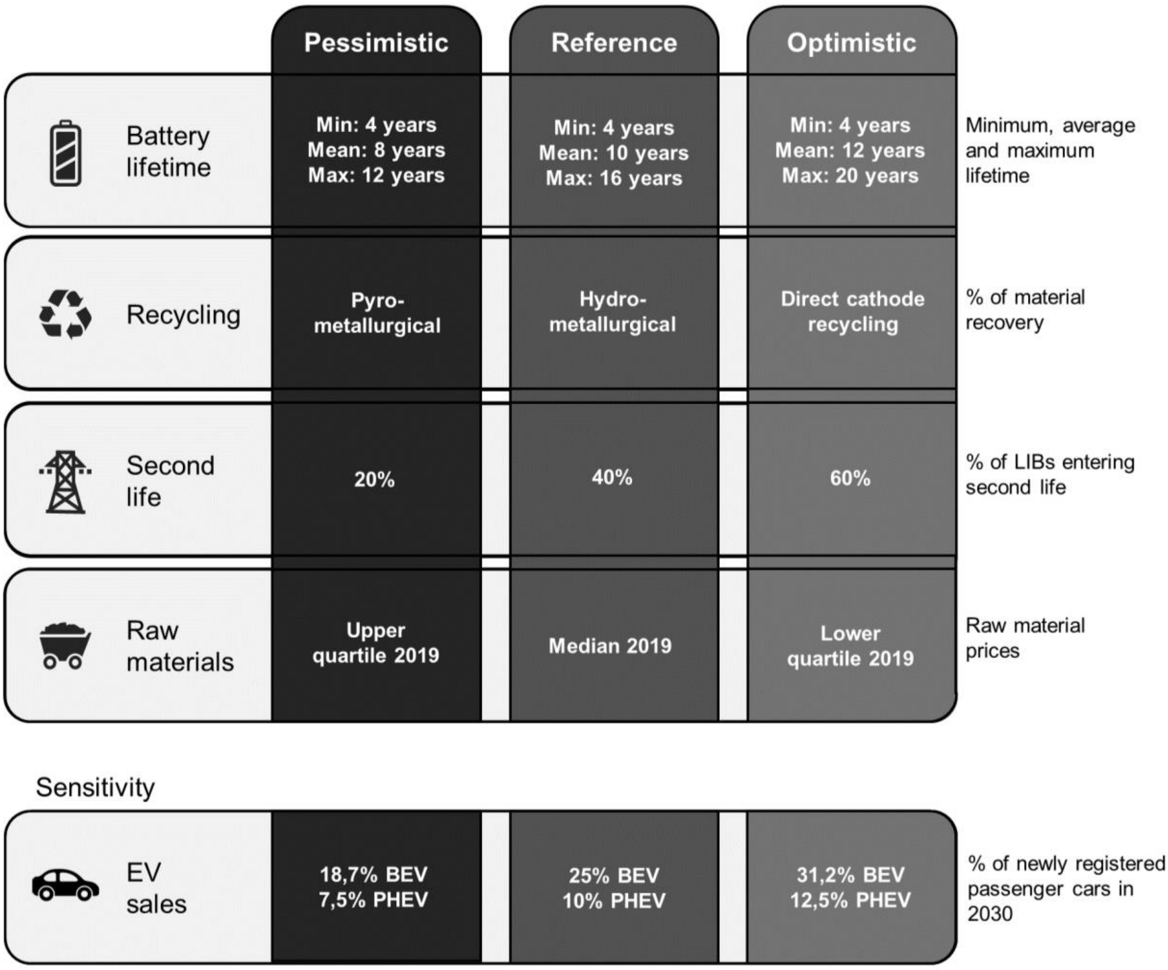


Figure 4.1.1 Dimensions and scenarios of the analysis.

4.2 Scenario analysis implementation

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. For example, for each of the three battery lifetime scenarios, all raw material price scenarios are applied, resulting in nine possible routes. For each of the nine combinations, three EOL scenarios (either recycling or reuse) are applied, resulting in 27 possible combinations.

The logic of the analysis is visualized in Figure 4.2.1.

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 figures, average battery size, and shares for different LIB chemistries. For the years 2011 to 2019, historic date was gathered, while for the 2020 to 2030, different approximations were made. 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 data includes sales projections for the years 2020 to 2023, which were used as a reference to create an extrapolation for the years 2020 to 2030 (numbers can be found in the following subchapters and in the Annex).

Sales of BEVs and PHEVs together with the average battery sizes then 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 additional information about each material, namely the material price (three scenarios) and the material environmental impact. Calculations are then performed to quantify the potential impacts of different recycling and reuse scenarios on economics, environment, and politics.

Afterwards, a sensitivity analysis is used to vary the number of EV sales 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 results.

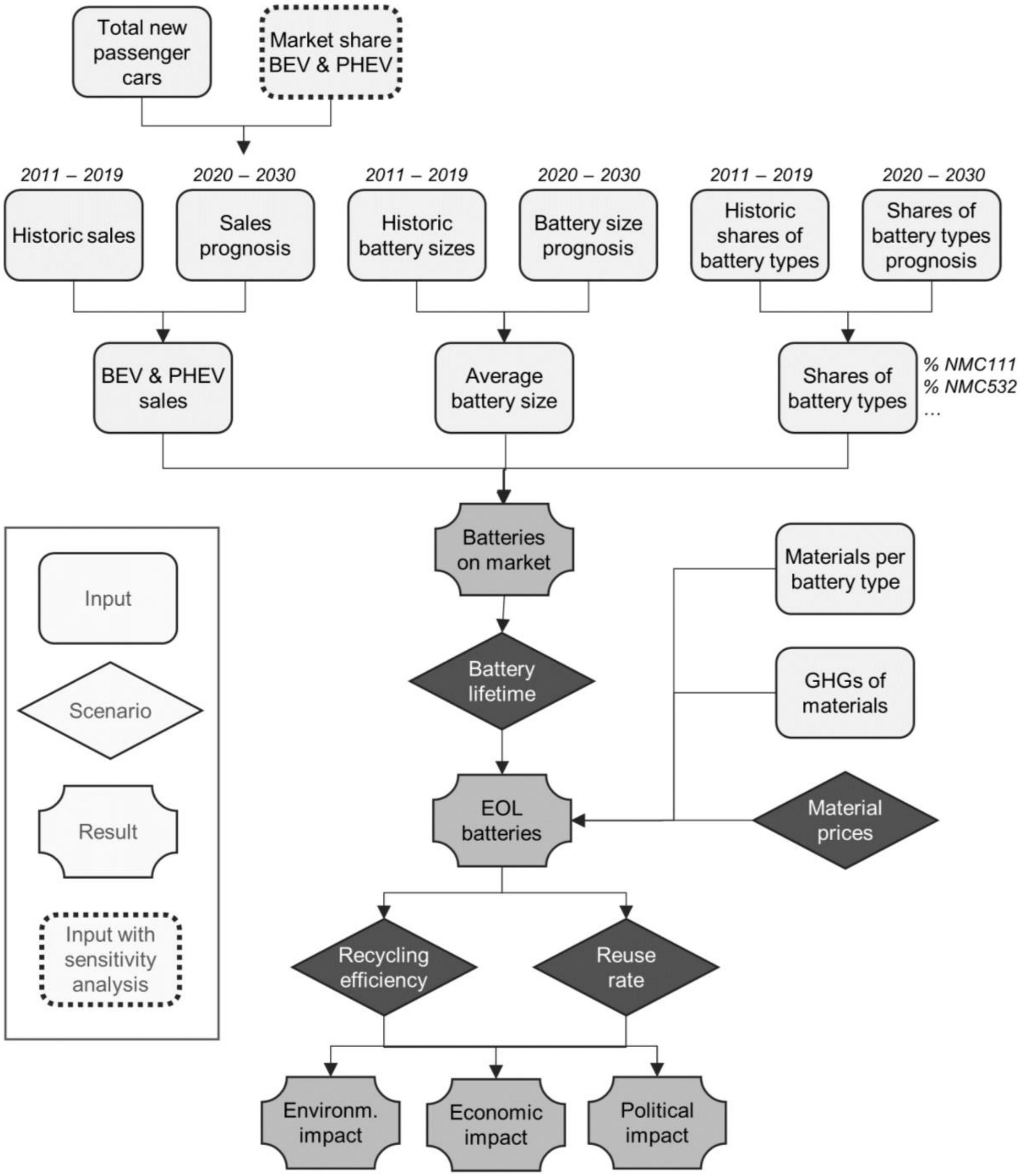


Figure 4.2.1 Schematic representation of the logic behind the analysis.

The following subchapter describe in more detail each of the different inputs that was used. For each input parameter, the limitations are stated to clearly show the level of accuracy.

4.2.1 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[12] (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%, whereas big differences existed among countries (EAFO 2020a). Historic numbers for the shares of BEVs and PHEVs from 2011 to 2019 can be seen in Table 4.2.1.

Table 4.2.1 Market share and number of vehicle registrations of newly registered passenger car BEV and PHEV vehicles in the EU from 2011 to 2019 (in % and number of sales, rounded).

	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEV	0,1%	0,1%	0,2%	0,3%	0,4%	0,4%	0,7%	1,0%	2,1%
	8.014	12.716	21.231	31.013	48.457	53.147	82.669	131.939	246.301
PHEV	0,0%	0,1%	0,3%	0,3%	0,6%	0,5%	0,7%	0,8%	1,2%
	-	8.025	24.922	25.485	71.186	65.387	86.446	108.197	140.384

Data source: (EAFO 2020a)

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 estimated 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 (see Table 4.2.2).

Table 4.2.2 Projection of market share of newly registered passenger car BEV and PHEV vehicles in the EU from 2025 to 2030 (in %, rounded).

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BEV	2,4	2,8	3,9	5,4	7,6	10,6	13,4	15,7	18,3	21,4	25,0
PHEV	1,4	1,6	2,0	2,5	3,1	4,0	4,8	5,7	6,9	8,3	10,0

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 2020a, 2020b, 2020c).

Market effects due to the Corona pandemic, such as reduction of production volumes and a decrease in demand are excluded since no reliable data is available at this point.

[12] "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.

4.2.1.1 Sensitivity analysis

The EV sales rate was estimated to have a large leverage on the overall results of the analysis while showing a great level of uncertainty. Meeting the EU targets was assumed as the reference case, but it is of further interest to analyze how a higher or lower rate of EV penetration would impact the results. Thus, it was decided to quantify the impact of the EV sales rate on the overall results by conducting a sensitivity analysis with two additional market growth scenarios. To create a pessimistic and optimistic scenario, the reference values were gradually increased and decreased to reach a 25% increase/reduction compared to the reference values by 2023 (see Table 4.2.3). The full table for all years can be found in Appendix Table A.2.

Table 4.2.3 Lower and higher scenario for the sensitivity analysis of the market share of newly registered passenger car BEV and PHEV vehicles in the EU from 2025 to 2030 (in %, rounded).

		2025	2026	2027	2028	2029	2030
Lower scenario	BEV	8,0	10,1	11,8	13,7	16,1	18,7
	PHEV	3,0	3,6	4,3	5,2	6,2	7,5
Reference	BEV	10,6	13,4	15,7	18,3	21,4	25,0
	PHEV	4,0	4,8	5,7	6,9	8,3	10,0
Higher scenario	BEV	13,3	16,8	19,6	22,9	26,8	31,2
	PHEV	4,9	5,9	7,2	8,6	10,4	12,5

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 (see Annex Table A.1) and thus PHEV emissions are expected to decrease further, and the large majority of 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. Nevertheless, a shift in modes of private transport, for example an increase in rail traffic could alter the number significantly. Furthermore, an economic crisis could lead to an abrupt reduction in sales, as seen after the financial crisis in 2008.

4.2.2 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 (see Table 4.2.4) 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.

The full table with values from 2011 to 2030 can be found in Annex Table A.1.

Table 4.2.4 Average battery size of newly registered BEV and PHEV passenger car electric vehicles in Europe from 2011 to 2019 (in kWh, rounded).

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
BEV	22	22	35	35	40	50	54	58	65
PHEV	-	11	12	11	12	12	12	13	13

Data source: (Takeshita et al. 2019)

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.
- The average battery size is used for all batteries that enter the market, independent from their cell chemistry.

4.2.3 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. LFP and LMO batteries were excluded since they represent a marginal share in the dataset of passenger car BEV and PHEV sales.

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 batteries 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}[13] 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.

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

Table 4.2.5 shows an extract of the results, displaying the market share values for BEV passenger car sales from 2011 to 2019.

Table 4.2.5 Market share of cathode chemistries for BEV passenger car sales from 2011 to 2019 (in %, rounded).

	2011	2012	2013	2014	2015	2016	2017	2018	2019
NMC111	100	84	49	51	42	20	4	2	1
NMC532	-	-	-	-	-	14	20	16	8
NMC622	-	-	-	-	-	2	23	29	36
NMC811	-	-	-	-	-	-	-	1	3
NCA	-	16	50	49	58	64	53	52	53

Own calculation based on: (Takeshita et al. 2019)

The future development of shares of battery chemistries for the years 2020 to 2030 (Table 4.2.6) was based on announced new EV models by the OEMs and sale projections until 2023 (Takeshita et al. 2019). Furthermore, the analysis in subchapter 2.1 of this thesis pointed out the trend of battery producers to produce higher nickel chemistries. 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 NMC 532 are assumed to fade out in 2024 and 2025 respectively, while NMC622 LIBs still hold a 10% market share in 2030. NCA batteries (predominantly used in Tesla vehicles) are assumed to lose their currently high market share due to the fact that other automotive companies increase their share of the EV market.

Table 4.2.6 Projection of market shares of cathode chemistries for BEV passenger car sales from 2020 to 2030 (in %, rounded).

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
NMC111	2	1	1	1	-	-	-	-	-	-	-
NMC532	11	6	3	3	2	-	-	-	-	-	-
NMC622	38	29	28	27	24	20	18	16	14	12	10
NMC811	10	30	41	45	52	60	64	68	72	76	80
NCA	39	34	27	24	22	20	18	16	14	12	10

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

The full table for both BEVs and PHEVs from 2011 to 2030 can be found in Annex Table A.4 and Table A.5.

Limitations:

- Changes of materials among the LIB chemistry types are assumed to be only in the cathode materials.
- 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.

4.2.4 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 (Tesla 2020; BMW 2020). 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[14] 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 (pessimistic, short lifetime scenario), 10 years (reference scenario), and 12 years (optimistic, long lifetime scenario). Furthermore, for each scenario it is assumed that 1% of batteries will reach their EOL already after 4 years of usage,

[14] 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.

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 each function, the percentage of batteries entering EOL $f(x)$ for each lifetime is calculated over the number of battery life years x.

$$Short\ lifetime\ scenario: f(x) = \frac{1}{1{,}65 * \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-8}{1{,}65})^2}$$
$$Reference\ scenario: f(x) = \frac{1}{2{,}5 * \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-10}{2{,}5})^2}$$
$$Long\ lifetime\ scenario: f(x) = \frac{1}{3{,}2 * \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-12}{3{,}2})^2}$$

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%, as depicted in Figure 4.2.2.

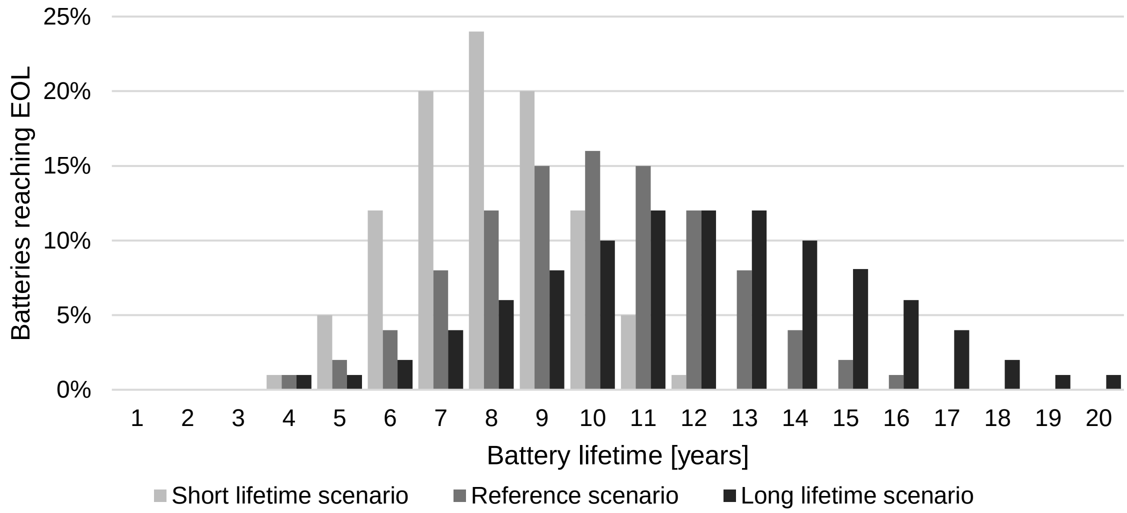


Figure 4.2.2 Scenarios for EV battery life distribution.

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.
- 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.

4.2.5 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 utilizes the weight shares presented in subchapter 2.1 for the NMC622 and the NCA battery, 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 the 8 materials presented in subchapter 2.2 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).

The detailed material compositions for the different LIB types can be found in Annex Table A.6.

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.

$$Cobalt_{2023,BEV,NMC111} = Co_{NMC111} \sum_{n=1}^{9} B_{tot,BEV,2020-n} * \%EOL_{after\ 3+n\ years} * \%NMC111_{BEV,2020-n}$$

$$= 0{,}313 \frac{kg}{kWh_{NMC111}} * (\underset{[2019]}{^{16GWh*1\%*1\%}} + \ldots + \underset{[2015]}{^{16GWh*24\%*42\%}} + \ldots + \underset{[2011]}{^{0{,}2GWh*1\%*100\%}})$$

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. A pseudo code of the VBA based implementation can be found in Annex C.

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.

4.2.6 Environmental impact of materials

The assessment of the environmental impact of mining and refining of battery raw materials follows the same approach as described in subchapter 2.2.1. It is based on the EU Environmental Footprint (EF) database, which provides the secondary data to calculate the EF of products in accordance with the PEFCRs. The data originates from different providers such as Thinkstep and ecoinvent.

GreenDelta, developer of the open source LCA tool OpenLCA, integrated the various EF datasets into one database called the “PEF database” (Recanati and Ciroth 2019), which can be downloaded free of charge at the openLCA Nexus platform (openLCA Nexus 2020).

When imported to openLCA (version 1.10.2), environmental impacts can be calculated using the PEF Environmental Footprint (mid-point indicator) LCIA method. For this analysis, only the impact category climate change will be assessed. The category is based on the baseline model of the IPCC 2013 and factors adapted from the Environmental Footprint guidance. Results are given in kg CO_2 equivalents.

The datasets are furthermore extended by values from the GREET model by Argonne National Laboratory in the US (Wang 2019). The median between PEFCR and GREET values was calculated to generate more robust results and not rely on a single source of information. Table 4.2.7 shows the inputs for this calculation.

Table 4.2.7 Different values for the climate change impact associated to eight LIB materials (in kg CO_2eq./kg material, rounded).

Aluminium	11,827 *PEF* *Aluminium sheet*	13,585 *PEF* *Aluminium foil*	8,082 *GREET* *Virgin wrought*	8,977 *GREET* *Virgin cast*
Graphite	2,654 *PEF* *Carbon black*	4,844 *GREET* *Graphite*		
Lithium	2,070 *PEF* *Lithium carbonate*	5,740 *PEF* *Lithium hydroxide*		
Nickel	10,707 *PEF* *Nickel*	8,739 *GREET* *Virgin nickel*	6,094 *GREET* *Virgin hydroxide*	8,739 *GREET* *Refined nickel*
Copper	3,474 *PEF* *Copper oxide*	2,522 *PEF* *Copper scrap*	3,023 *GREET* *Copper*	
Steel	2,747 *PEF* *Cold rolled coil*	3,091 *GREET* *Virgin steel*		
Cobalt	36,053 *PEF* *Cobalt*	18,151 *GREET* *Virgin cobalt oxide*	8,360 *GREET* *Virgin cobalt chloride*	21,001 *GREET* *Virgin cobalt metal*
Manganese	12,456 *PEF* *Manganese*	8,730 *GREET* *Manganese*		

Data source: (GreenDelta GmbH 2020) (Wang 2019)

The focus of the environmental analysis lays on the material inside LIBs. To furthermore provide an estimation of the overall battery lifetime emissions, rough approximations are made for battery production, recycling process and refurbishment for second life. Those approximations derive from the numbers presented earlier, see subchapter 2.3.2 (emissions of manufacturing), 3.1.3 (emissions of second life refurbishing), and 3.2.5 (emissions of recycling processes). For the production and recycling processes, the GHG emissions are calculated by multiplying the assumed energy demand with the average GHG emissions of the European electricity mix. For the emissions associated for refurbishment, it is assumed that they are made up solely of the emissions associated to the new materials which are added. Table 4.2.8 summarizes the assumed numbers.

Table 4.2.8 Emissions associated to battery production battery refurbishment and recycling (in kg CO_2eq./kWh, rounded).

Battery production	25,251		
Battery refurbishment	15,145		
Recycling	7,820 *Pyrometallurgical*	3,432 *Hydrometallurgical*	2,717 *Direct cathode*

Own calculation based on: (Wang 2019), (GreenDelta GmbH 2020).

Limitations:

- There is no universally accurate data on emission associated with raw material. Each data provider uses different means of data collection and sets different limitations. At the same time, the exact composition or grade in which each material enters the production process is unknown. Thus, a mean value was generated from different input sources and with varying material grades to increase the reliability. Nevertheless, the calculated values are prone to errors.

- The assumed emissions for battery production, battery refurbishment and recycling are rough estimation with little validity. For reliable approximations, further studies on the environmental impacts of these processes are needed.

4.2.7 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.

Subchapter 2.2 discussed the raw materials inside LIBs and showed the great variations of economic impact. While cobalt, nickel, lithium and copper are the highest priced materials, graphite, steel, aluminium and manganese only have a small impact on the price of the battery.

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 (Table 4.2.9). The period for the historic values was set to 2019, since it was the only full year for which all data points were available.

Table 4.2.9 Material price scenarios based on 2019 monthly market prices (in €/kg, rounded).

		Pessimistic scenario	Reference scenario	Optimistic scenario
Material	**Market Commodity**	**Lower quartile**	**Median**	**Upper quartile**
Aluminium	High grade primary aluminium	1,580	1,597	1,617
Graphite	Crystalline large flake graphite, 94-97%	0,718	0,739	0,782
Lithium	Lithium carbonate, min. 99,5%	7,417	9,286	9,930
Nickel	Primary nickel, min. 99,8%	10,956	11,700	13,719
Copper	Grade A copper	5,233	5,257	5,485
Steel	HRC steel	0,459	0,497	0,542
Cobalt	Cobalt, min. 99.8%	26,996	30,218	31,663
Manganese	Electrolytic manganese, min. 99,7%	1,484	1,704	1,733

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.

4.2.8 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. Three different technologies were presented in subchapter 3.2: pyrometallurgy, hydrometallurgy and direct cathode recycling.

The three scenarios for the recycling of LIBs are defined as the three recycling technologies with their varying material recovery rates (Table 4.2.10). The focus hereby lays on the metals and graphite. The values 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. It should be noted that state-of-the-art processes such as the one implemented by Duesenfeld in Germany already achieve higher recovery rates.
Direct cathode recycling is estimated to have the same recovery rates as hydrometallurgy but will regenerate the cathode active materials together.

Table 4.2.10 Material recovery efficiencies for the three recycling scenarios.

	Pessimistic scenario	Reference scenario	Optimistic scenario
	Pyrometallurgy	**Hydrometallurgy**	**Direct cathode recycling**
Aluminium	0%	90%	90%
Graphite	0%	90%	90%
Lithium	0%	90%	(full cathode recovery)
Nickel	98%	98%	(full cathode recovery)
Copper	90%	90%	90%
Steel	90%	90%	90%
Cobalt	98%	98%	(full cathode recovery)
Manganese	0%	98%	(full cathode recovery)

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).

4.2.9 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. 2015b).

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.

5 Results and discussion of scenario analysis

The results of the scenario analysis are divided into 4 thematic sections.

- 1st: The estimation of battery demand and number of batteries entering the market.
- 2nd: The number of batteries reaching their EOL.
- 3rd: The implications of recycling EOL batteries.
- 4th: The impacts of reusing LIBs after their first life, prior to recycling.

The same order is followed when discussing the results of the sensitivity analysis. After presenting the scenario results, a separate chapter is summarizing the findings and discussing political implications, followed by a chapter on related works .

5.1 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 (Annex Table A.1), the required battery production capacity to meet the EU demand was calculated. The filled grey bar charts in Figure 5.1.1 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.

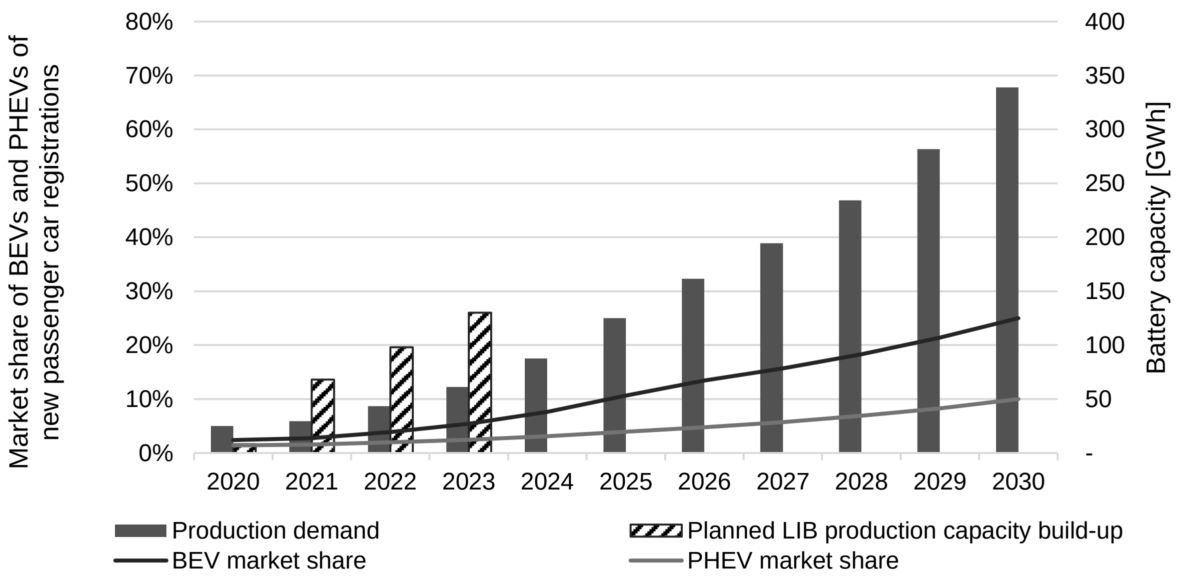


Figure 5.1.1 LIB market scenarios for BEVs and PHEVs in EU. Left axis: Market shares of BEVs and PHEVs of newly registered passenger cars in the EU; Right axis: LIB production capacity necessary to meet BEV and PHEV passenger car demand (in GWh) and announced production build-up (non-exhaustive).

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 (see Table 5.1.1).

Table 5.1.1 LIB demand in the EU 2020, 2025 and 2030, based on the conducted analysis (in kWh, rounded).

2020		2025		2030
25.068.045	→	125.057.344	→	338.988.147

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 (Lebedeva et al. 2018), LG Chem is building their largest global LIB production facility in Poland with a capacity of 65 GWh (EIB 2020), and in Germany several LIB production plants are currently under construction. CATL is constructing a 24 GWh plant in Erfurt (CleanTechnica 2019), Farasis builds a 10 GWh facility in Bitterfeld-Wolfen (Press Office Saxony-Anhalt 2019), and VW created a joint venture with Northvolt to create a 16 GWh LIB plant in Salzgitter (Volkswagen 2019). 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 5.1.1). 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.

Additional graphs showing the number of newly registered vehicles against the battery production demand, and the development of the average battery sizes can be found in the Annex (Figure B.1 and Figure B.2).

5.2 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 (see Table 5.2.1).

Table 5.2.1 EOL LIBs in the EU in 2020, 2025 and 2030 for 3 different lifetime scenarios (in kWh, rounded).

	2020		2025		2030
Short lifetime	670.511		7.908.865		50.946.682
Base case	299.352	→	4.218.108	→	30.573.453
Long lifetime	167.777		2.497.688		19.124.692

Figure 5.2.1 visualizes the results for the three different lifetime scenarios. The graph shows 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.

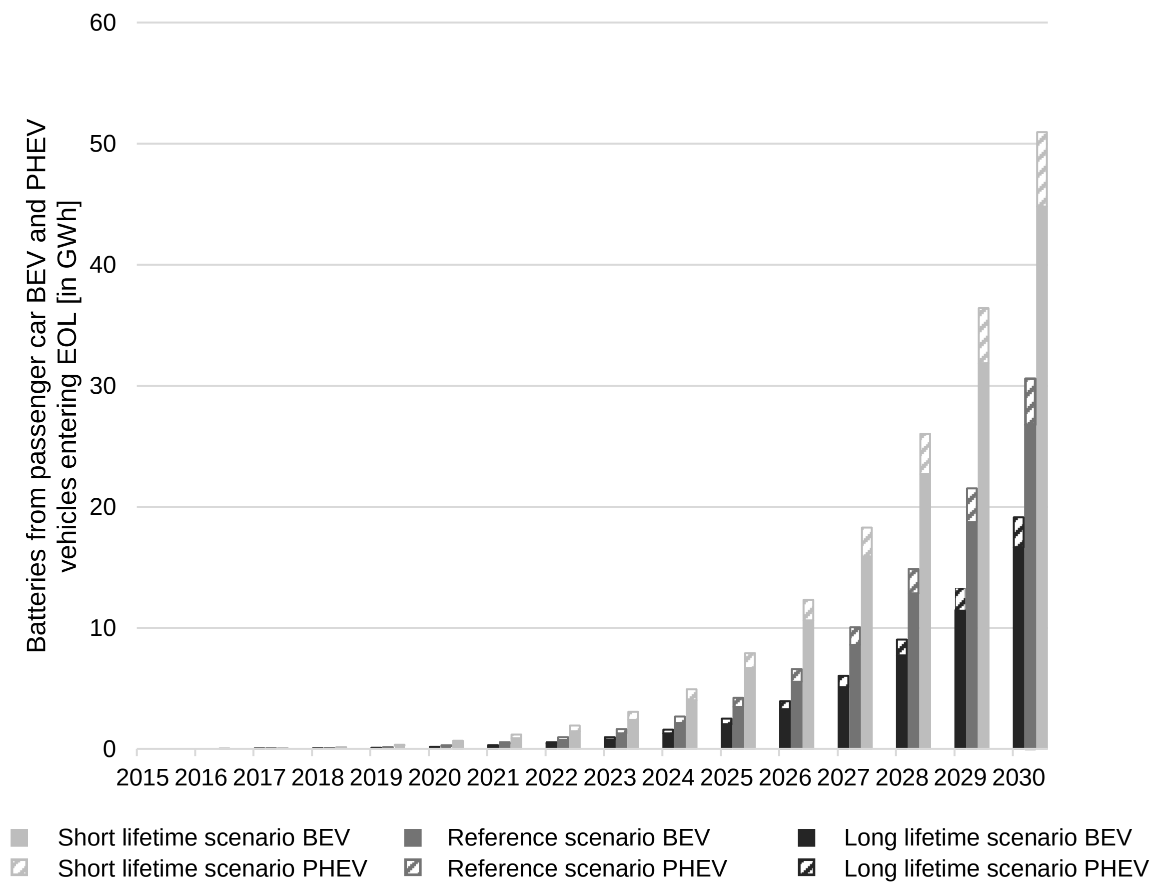


Figure 5.2.1 EOL vehicle stream in GWh for BEV and PHEV passenger cars for 3 different battery lifetime scenarios, all with the base case market share scenario to reach 35% BEVs and PHEVs in 2030. The battery capacity refers to the capacity of the batteries at market entry.

The large uncertainties both about the EV uptake and the lifetime of batteries make business decisions on reuse and recycling of EOL batteries difficult. Better knowledge about battery lifetime is needed to improve projections.

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 5.2.2 shows the battery demand versus the capacity of batteries entering their EOL. The graph shows that for the given scenarios the capacity of EOL batteries can cover around 10% of the EU battery demand in 2030. Thus, a large dependence on virgin raw materials will continue to exist, even if a circular flow of EOL battery materials is reached. While some domestic projects are evaluating European mining for e.g. lithium, the import of raw materials from outside Europe will remain an essential part of the battery value chain in the years to come. A truly circular LIB value chain in Europe can only be achieved once the number of EVs in the market stabilizes.

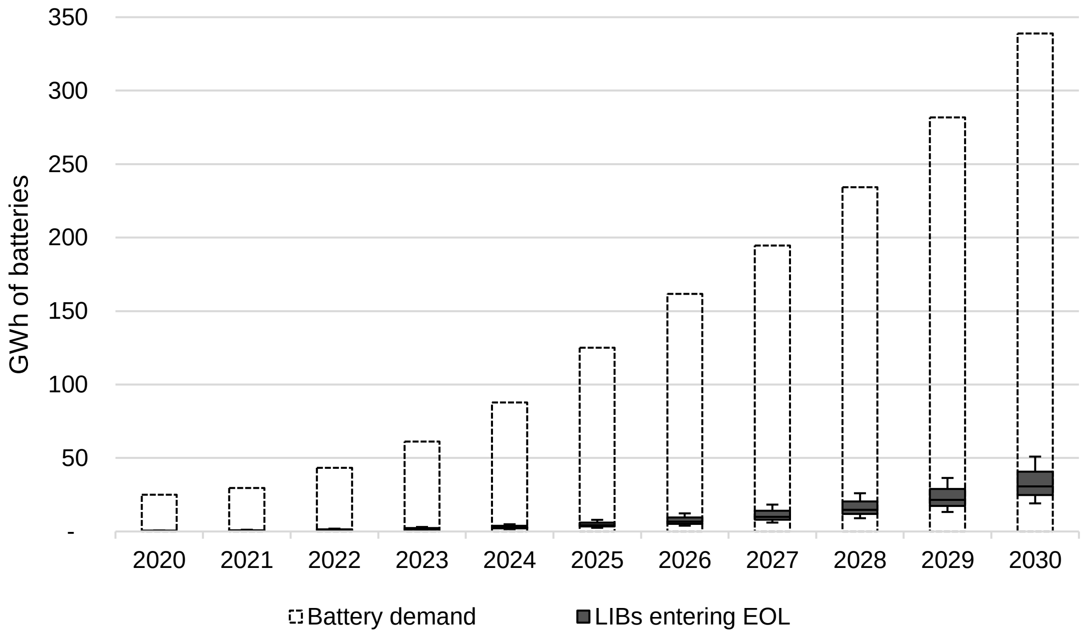


Figure 5.2.2 Battery demand and EOL batteries (capacity fade unconsidered) for three lifetime scenarios from 2020 to 2030.

While Figure 5.2.2 showed the overall battery capacity, Figure 5.2.3 and Table 5.2.2 show the differences among the materials per kg. Based on the different scenarios, the material demand for battery production is plotted against the theoretical maximum supply of raw materials from EOL batteries for cobalt and nickel. Not only absolute numbers differ, but also the percentages of materials demand that can be covered by EOL materials.

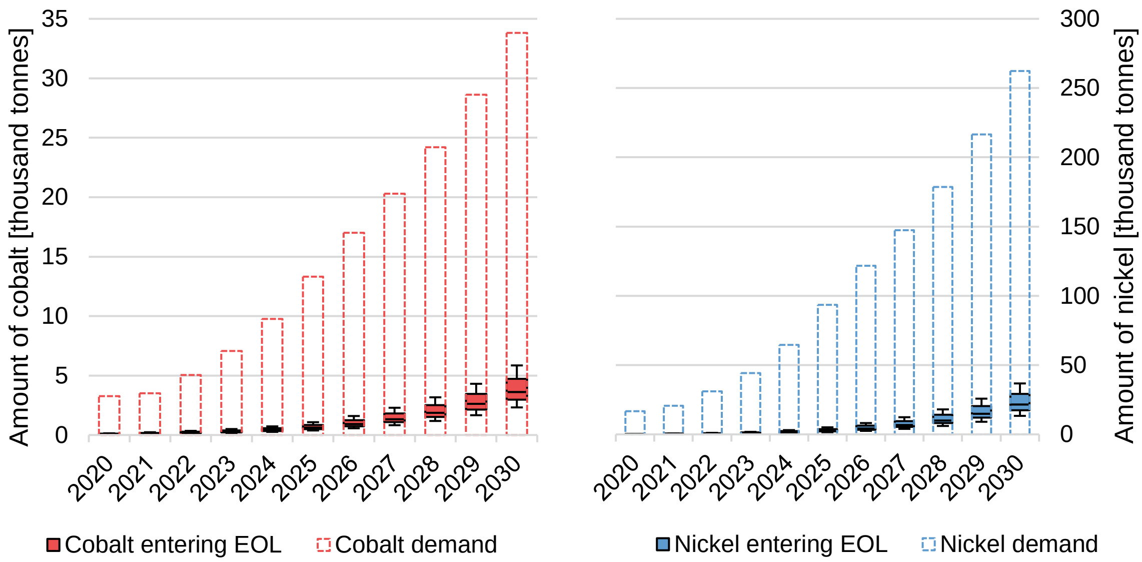


Figure 5.2.3 Material demand and EOL materials (3 lifetime scenarios) for cobalt and nickel from 2020 to 2030.

The trend in LIB cell chemistries towards lower cobalt contents reduces the amount of cobalt that is required per battery. At the same time, the nickel share inside newly produced LIBs is rising. Table 5.2.2 shows the share of material demand for battery production that could theoretically be covered by the materials inside EOL batteries with the mean value of the 3 lifetime scenarios (assuming a 100% recovery rate and battery grade quality of the recycled materials). Cobalt (10,7%), manganese (10,5%) and steel (11,3%) show the highest share of potential material supply from EOL vehicles. For cobalt and manganese, this is due to the diminishing material shares within the modern NMC LIB chemistry types. For steel, this is due to the proportionally reducing share of NCA batteries in BEVs which contain higher shares of steel per kWh of battery. While Tesla long dominated the EV sales with their NCA type batteries, the other OEMs, which almost exclusively use NMC batteries, are expected to regain market shares.

Table 5.2.2 Share of material demand for battery production that could, based on the mean value of the scenario results, be covered by EOL batteries in the EU (in %, rounded).

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Aluminium	1,2	1,9	2,2	2,7	3,0	3,4	4,1	5,2	6,3	7,6	9,0
Graphite	1,2	1,9	2,2	2,7	3,0	3,3	4,0	5,1	6,3	7,6	9,0
Lithium	1,2	1,9	2,2	2,6	3,0	3,3	4,0	5,0	6,2	7,4	8,8
Nickel	0,9	1,4	1,7	2,1	2,5	2,8	3,5	4,5	5,6	6,9	8,2
Copper	1,2	1,8	2,1	2,5	2,8	3,1	3,8	4,8	5,9	7,1	8,5
Steel	1,2	2,0	2,6	3,3	3,9	4,4	5,3	6,7	8,2	9,7	11,3
Cobalt	2,0	3,2	3,6	4,0	4,4	4,7	5,4	6,5	7,8	9,2	10,7
Manganese	2,0	3,2	3,7	4,0	4,4	4,8	5,5	6,6	7,8	9,1	10,5

Compared to cobalt, manganese and steel, the share of nickel that could potentially be extracted from EOL batteries to supply the battery production is lower and accounts for 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.

5.3 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 5.3.1 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.

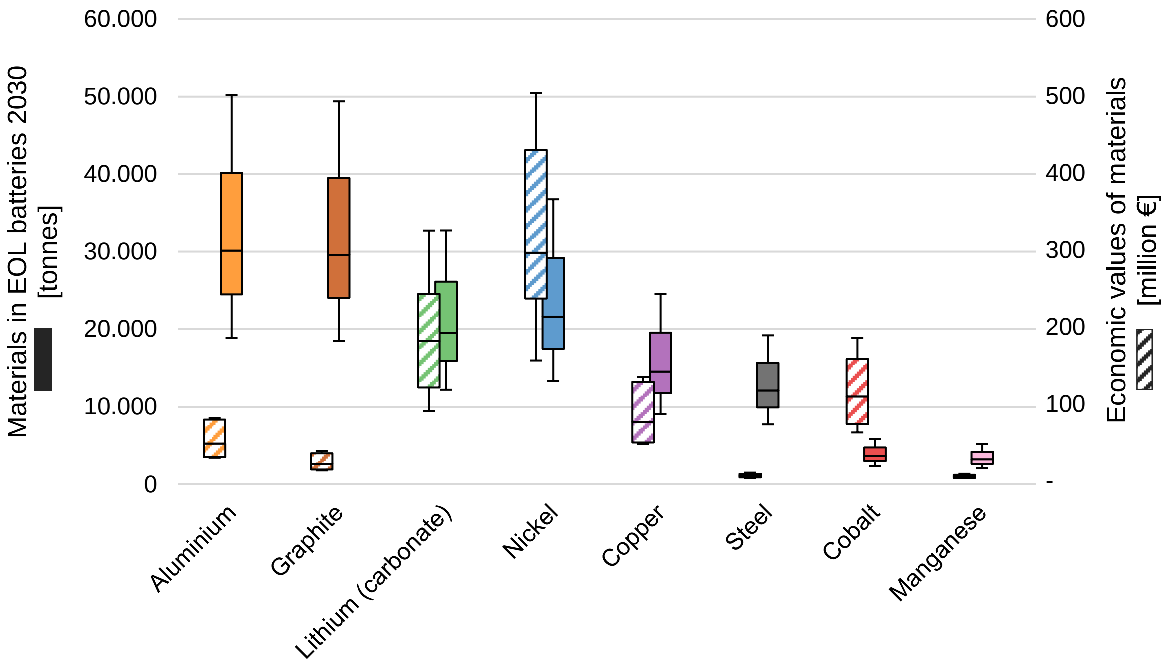


Figure 5.3.1 Materials inside LIBs that reach their EOL in 2030, and the corresponding economic value. Results for 3 lifetime and 3 raw material price scenarios.

Graphs for 2020 and 2025 can be found in the Annex (Figure B.3, Figure B.4).

The graph furthermore shows the impact of chemistry changes towards lower cobalt contents. Even though cobalt is by far the highest priced material (see subchapter 2.2), the economic importance within the LIB materials is reducing over the years. Figure 5.3.2 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.

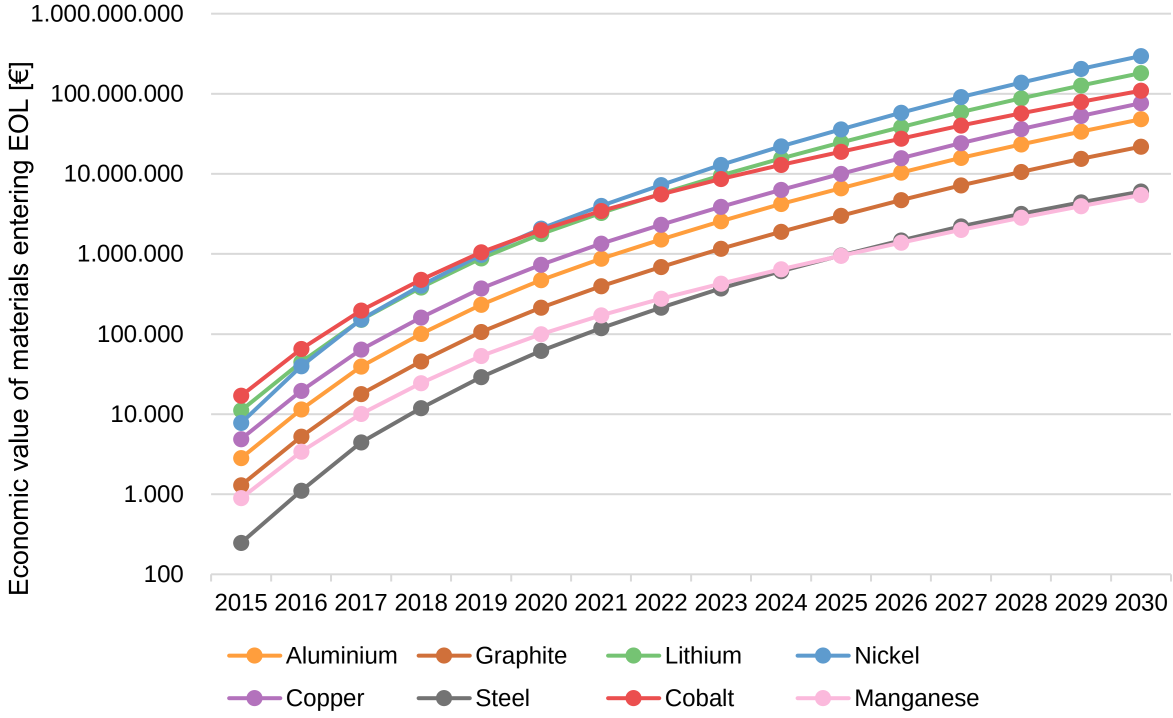


Figure 5.3.2 Economic value of materials in EOL batteries from 2015 to 2030. Median of results of 9 scenarios for each of the materials (3 lifetime, 3 raw material price scenarios).

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 5.3.3, calculated with mean value of the scenario results).

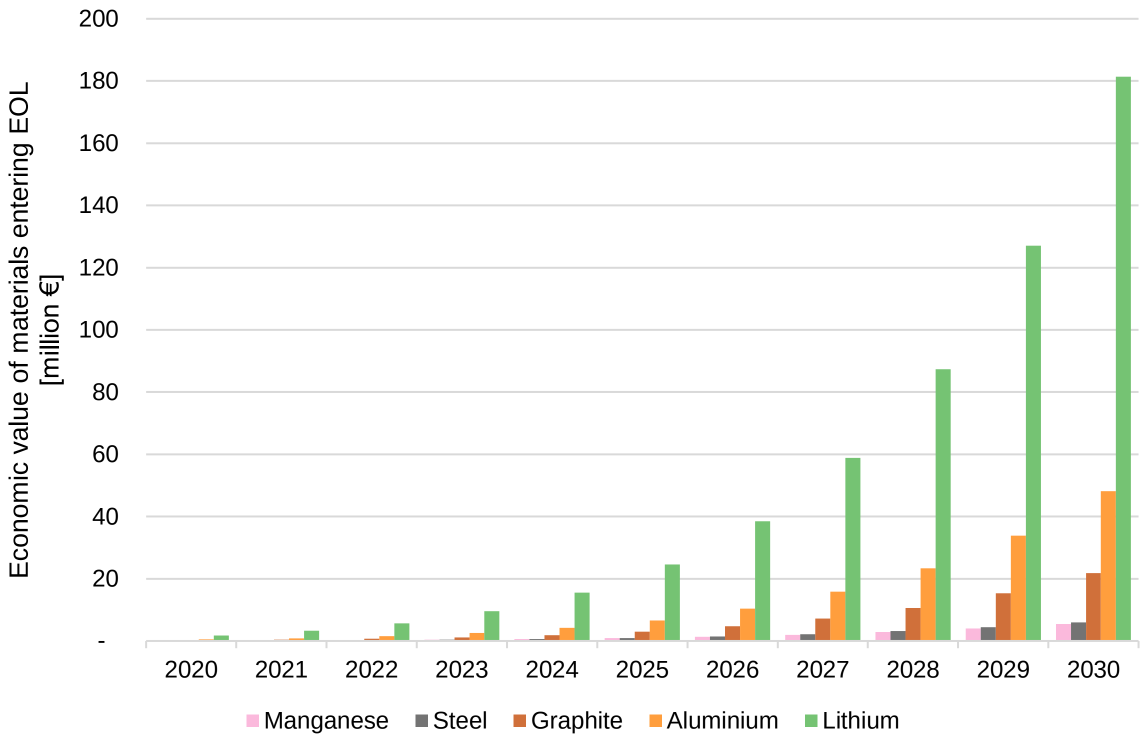


Figure 5.3.3 Economic value of lithium, aluminium, graphite, steel and manganese in EOL batteries from 2020 to 2030. Mean value of the results of 9 scenarios for each of the materials (3 lifetime, 3 raw material price scenarios).

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 will move out of the research state soon. Recyclers must deal with the constantly changing cathode chemistries, which favors universally applicable technologies. 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.

Besides the political interest to achieve high recycling rates, the environmental impact of recycling versus virgin material mining and processing must be positive. Subchapter 3.2.5 indicated low emissions of the recycling processes, but further assessments are needed to validate the results for specific processes.

5.4 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 5.4.1 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. To put this into context: The European Wind Energy Association (EWEA) estimates that an average onshore wind turbine with a capacity of 2,5 to 3 MW can produce more than 6 million kWh electricity in a year (EWEA 2020), which translates to 16.438 kWh per day (note that for windy days this value will be exceeded). The 24,8 GWh battery storage from second life batteries could thus store the daily production of 1.508 windmills, a number that is sufficient to supply 2,3 million average European households with electricity (1.500 households per wind turbine (EWEA 2020)).

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

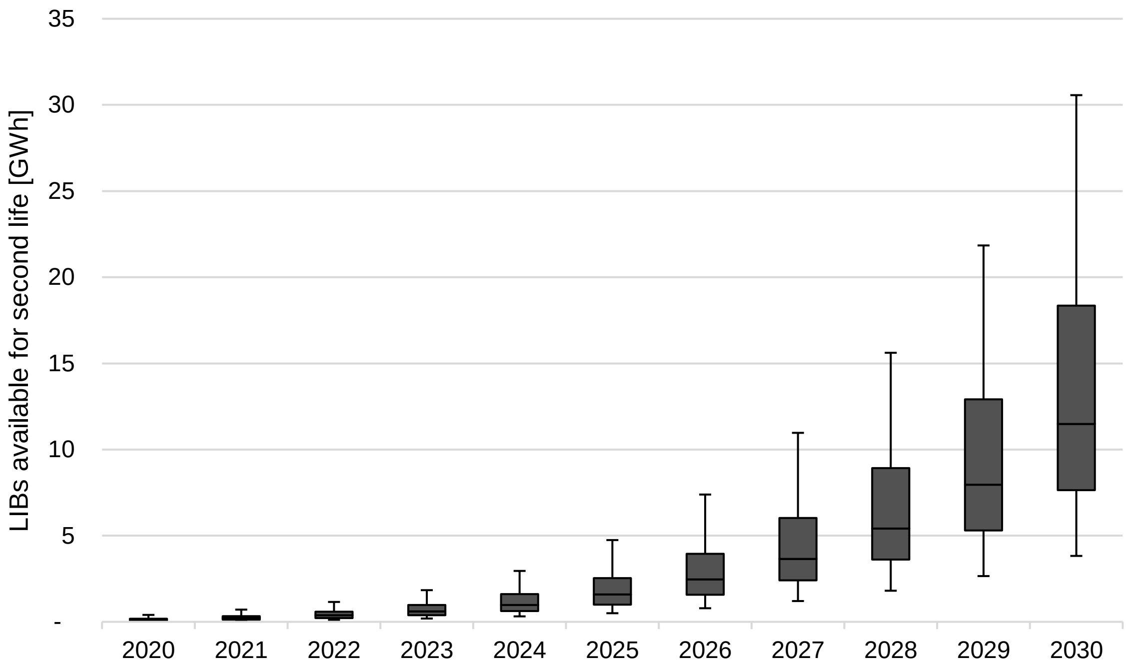


Figure 5.4.1 GWh of LIBs eligible for second life from 2020 to 2030. Results for 9 scenarios (3 lifetime, 3 reuse scenarios).

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.

Nevertheless, from the environmental perspective, a reuse of LIBs is likely to be beneficial since emissions for the energy intensive battery production are avoided. To compare the emissions associated with different processes during the battery first and second life, the emissions were calculated and plotted in Figure 5.4.2. It should be noted that the numbers for the environmental impacts are approximations that were made with great simplifications.

The raw material emissions represent the emissions related to mining and refining of the raw materials and are derived from the NMC622 material composition (Annex Table A.6) and the environmental impacts from the EU PEF LCA database (Annex Table A.7).

The battery production emissions solely represent the energy consumption of the production process under the assumption that all energy is supplied by electricity and with an average European electricity mix (see subchapter 2.3.2 and 4.2.6).

Emissions caused during the first lifetime (as an EV battery) and second lifetime (as stationary storage application) are excluded since the focus is on the comparison within different LIB life stages and not the comparison to other forms of transport or energy storage.

Moreover, the graph does not show the emissions related to transport. Raw materials are transported long distances from the mining site to the refining facilities and finally to the battery production factory. Batteries are furthermore delivered to the vehicle OEMs after production and must be collected after the first and second life. However, emissions related to transport are very small compared to those of industrial processes. As shown in subchapter 3.1.3, emission related to a 100 km truck transport result in emissions of only 0,028 kg CO_2 per 1 kWh of NMC622 LIB. Longer transport distances from raw materials that are sourced outside of Europe are normally covered by ship transport, which show much smaller emissions per kg of cargo compared to transport by road. Thus, emissions related to transport will only cover a marginal share and therefore it is deemed acceptable to exclude them from the graph.

After a lifetime of 4 to 20 years, the batteries will be repurposed.

The emissions of repurposing are approximated only with the demand of new materials which are needed to create the refurbished LIB pack (see subchapter 3.1.3), namely an new BMS, thermal management system and casing materials on pack level. Thus, the displayed emissions are not considering the emissions related to the repurposing process itself, since no reliable data was found.

After another 10 years of second life in a stationary storage application, the batteries are recycled to recover the materials.

The emissions of recycling are approximated by the process energy demand under the assumption that all energy is supplied by the average European electricity mix (see subchapter 3.2.5).

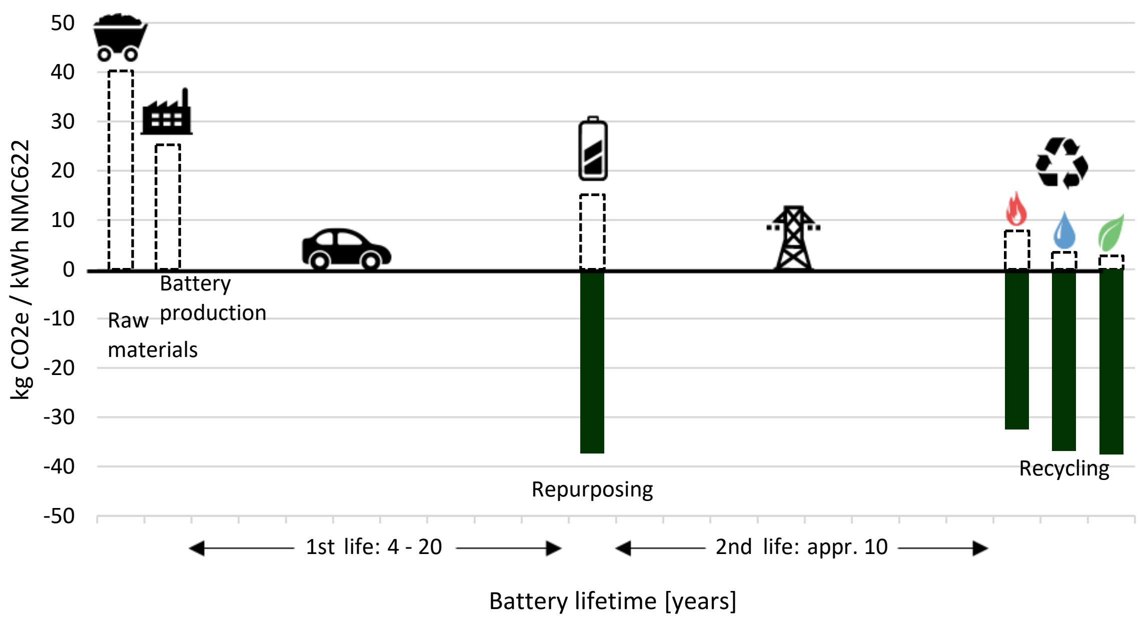


Figure 5.4.2 Lifetime emissions of NMC622 LIB. Includes estimated emissions of raw material mining, battery production, repurposing and 3 different recycling processes (pyrometallurgic, hydrometallurgic, direct cathode recycling). Excluded are transport and use phase emissions.

Figure 5.4.2 shows the highest emissions linked to the raw material mining and refining (high data reliability due to the usage of a professional LCA database). The battery production process also causes high emissions, but around 30% lower compared to the raw materials (low data reliability due to insufficient data on emissions of actual production processes in Europe; only the energy demand is counted which was calculated using BatPaC). It should be noted that the emissions caused by battery production can be strongly reduced if the process is fueled by renewable energy, as implemented by Northvolt in northern Sweden (the manufacturing plant is powered by hydropower (European Commission 2018)).

Both the reuse (very low data reliability) and the recycling process (low data reliability) causes low emissions compared to raw materials and battery production. Furthermore, these processes save emissions by avoiding the usage of virgin raw materials (both for reuse and recycling), and additionally avoid large parts of the battery production process (reuse). The net environmental benefit is plotted on the negative part of the y-axis. For the environmental benefit of repurposing, the repurposed battery is assumed to replace a new battery with the same capacity as the repurposed battery (80% of initial capacity). Thus, the emissions related to such a newly produced battery (emissions of raw material demand and battery production) are subtracted from the emissions caused by the repurposing (on positive y-axis). For the recycling, the emissions related to raw material mining are subtracted from the emissions related to the recycling process.
It should again be noted that the processes of repurposing and recycling represent rough approximations and require improvements in data quality (see subchapter 4.2.6).

Despite the unreliability of the numbers presented in Figure 5.4.2, the graph can foster the discussion about LIB EOL alternatives. The difference between emissions of repurposing and battery production encourages further investigation of second battery life, and the large reduction of recycling emissions compared to emissions related to virgin materials strongly suggests to encourage high quality recycling processes.

5.5 Sensitivity to EV uptake

To analyze how the scenario results are impacted by a change in the number of newly registered vehicles, a sensitivity analysis was carried out. Two additional scenarios were defined for the EV uptake, gradually increasing to reach a 25% increase and 25% reduction compared to the reference case in 2023 (see subchapter 4.2.1.1). The following subchapters present the variations in the results caused by changes to the EV uptake.

5.5.1 Battery demand and supply

The battery demand directly reflects the changes to the EV uptake of the sensitivity analysis. A 25% increase in BEV and PHEV registrations results in a 25% increase in battery demand. However, even with this strong increase, the planned buildup of domestic battery production facilities in the EU will be sufficient to meet the market demand for passenger vehicles BEV and PHEV batteries. The production capacity buildup of 130 GWh by 2023 can easily cover the demand of 76 GWh in 2023, even for the high market share scenario. Further graphs and tables visualizing the result can be found in the Annex (Table A.10, Figure B.5).

5.5.2 End-of-life batteries

With the 3 market share scenarios and 3 LIB lifetime scenarios, a total of 9 different scenarios for the number and size of EOL batteries was calculated. The additional scenarios increase the range of values less than one could expect. From initially a minimum of 2,5 GWh and a maximum of 7,9 GWh in 2025 the range of values increases in the sensitivity analysis to a minimum of 2,4 GWh and a maximum of 8,1 GWh.

In 2030, the range of values expands from 19,1 GWh and 50,9 GWh to 16,2 GWh and 61,9 GWh (see Table 5.5.1). Due to the long average battery lifetime, the impact of the number of registered vehicles is delayed by several years and furthermore softened by the lifetime distribution functions.

Table 5.5.1 EOL LIBs in the EU in 2020, 2025 and 2030 for 9 different scenarios (in kWh, rounded).

		2020		2025		2030
Lower market share	**Short lifetime**	670.511		7.739.199		40.018.211
	Reference	299.352	→	4.123.646	→	25.335.979
	Long lifetime	167.777		2.428.294		16.231.674
Reference	**Short lifetime**	670.511		7.908.865		50.946.682
	Reference	299.352	→	4.218.108	→	30.573.453
	Long lifetime	167.777		2.497.688		19.124.692
Higher market share	**Short lifetime**	670.511		8.078.531		61.875.153
	Reference	299.352	→	4.312.570	→	35.810.927
	Long lifetime	167.777		2.567.082		22.017.711

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 also better data on the export of old vehicles outside of Europe.

While the sensitivity analysis showed a small impact on the EOL batteries in the near-term future, Figure 5.5.1 shows the large variations in battery demand that are caused by the changes in vehicle registrations. The different scenarios for vehicle registrations cause a battery demand that varies more than 150 GWh in 2030, making business decisions very difficult. To put this into context: the 6 large scale battery production plants currently in construction in different European countries (see subchapter 5.1) will only have a combined capacity of 130 GWh.

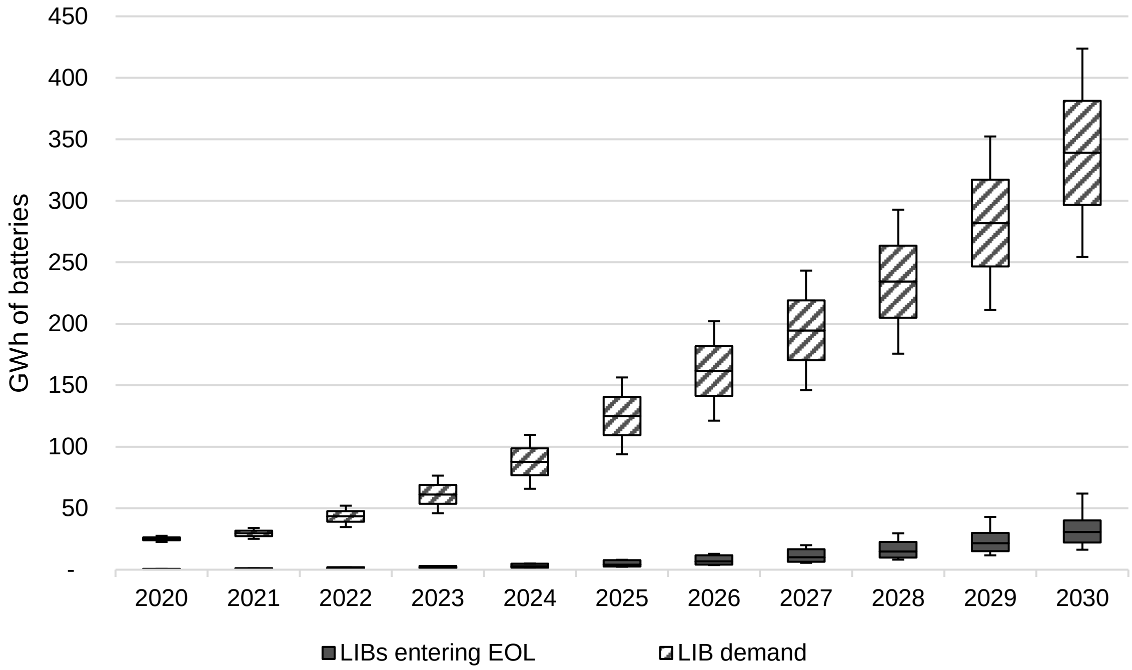


Figure 5.5.1 Sensitivity result for battery demand and EOL batteries (no capacity fade) for 3 market share and 3 lifetime scenarios from 2020 to 2030.

5.5.3 Recycling

The number of LIB that reach EOL is only impacted 4 years after vehicles enter the market, and so are the materials. Like the number of EOL batteries, the amount of materials that are eligible show little influence by the change in newly registered vehicles until the mid-2020s. The increase of material amounts compared to that of the reference market share scenario progresses slowly from less than 1% change in 2024 to about 21% in 2030. By then the influence of the input variable shows a large impact on the economics of recycling, as seen in Figure 5.5.2. The economic value that could potentially be found in EOL batteries in 2030 then ranges from 132 million € to 613 million € for nickel (compared to 156 million € and 504 million € for the reference market share scenario).

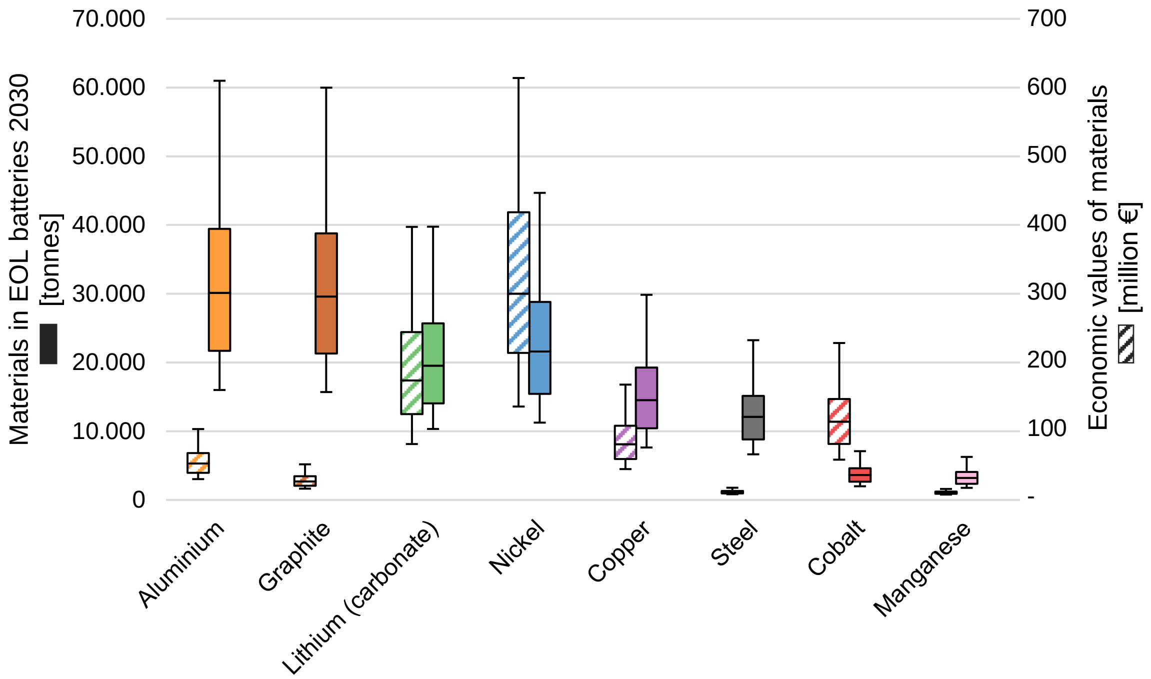


Figure 5.5.2 Materials inside LIBs that reach their EOL in 2030, and the corresponding economic value. Sensitivity results for 3 market share, 3 lifetime and 3 raw material price scenarios.

Nevertheless, the number of materials that will enter EOL shows the delay of the battery lifetime which gives recyclers the opportunity to estimate the number of batteries that will retire in the upcoming years accurately if other input variables are known. Especially knowledge about the battery lifetime will be an important key to predicting the market for recycling and second life.

5.5.4 Second life

Similarly, to the recycling sector, the number of second life batteries is only impacted by the change in EV uptake with a delay of several years. A graph of the GWh eligible for second life when including the scenarios of the sensitivity analysis can be found in Annex Figure B.6.

When imaging a coupling of reuse and recycling of EOFL batteries, the volumes of batteries eligible for recycling will be impacted strongly. For the share of EOFL batteries that enter a second life, the recycling process will be delayed by the time of the second life. This adds additional factors of uncertainty to the prediction of potential recycling volumes, such as the lifetime of the second life application, or the collection rate after both first and second life. While it will be environmentally beneficial to reuse batteries, it could potentially hamper the development of the recycling industry. At the same time, a delay in EOL battery volumes gives recyclers the opportunity to further improve recovery rates of their processes. Once the reused batteries will then enter the recycling process, fewer materials will be lost.

5.6 Discussion of political implications

The revised EU Battery Directive is under preparation and expected to be adopted in the following months. Areas with need of improvement have been identified as for example the collection and recycling rates. The Commission stated that “current minimum collection targets […] and the minimum recycling requirements are not appropriate” (European Commission 2019c). While all batteries already have to undergo an EOL treatment, the current legislation does not specify efficiency targets for specific materials other than lead and cadmium, which have no relevance for LIBs. With reference to the European goal of a circular economy, the current Directive is said to be “insufficiently equipped to easily incorporate technical novelties” (European Commission 2019c). This includes the distinctions between novel battery types (LIBs are not mentioned) and the possibility of a second life.

The results of the scenarios developed in this thesis show versions of the future with a LIB market in Europe full of market opportunities but also with areas in need for improvements. As such, the results indicated political implications which are discussed in the following paragraphs. The discussion is classified under the category’s raw materials, battery production, recycling and second life.

Raw materials

A large EU import dependency on LIB materials was detected. As long as battery demand and battery sizes are growing, the EU dependence on import of raw materials for battery production will continue to exist. Nevertheless, the material demand can increasingly be covered by recycled materials if the materials inside EOL batteries are recovered. In the depicted scenarios, EOL batteries were able to cover a theoretical maximum (assuming 100% collection rate and 100% recycling efficiency) from 9 to 11% of material demand in 2030. These quantities translate to several hundred million Euros in economic value.

Furthermore, several European projects currently examine the possibility to explore local reserves of minerals such as lithium and graphite which show high import reliance’s (see subchapter 2.2). Policy makers should further encourage domestic mining projects to increase the share of European mined minerals in the European battery production. At the same time, raw material refining capacities need to be implemented. If mined materials have to be exported to China to be refined, to then travel back to Europe, benefits in terms of environmental impacts and supply risk are diminished. At the same time, local mining sites should be assessed in terms of their environmental impact. While lithium mined from brines in South America is very energy efficient, mining of lithium in Europe from hard rocks could cause emissions exceeding those of importing the materials from oversees, even when transport is included.

Battery production

The scenarios suggested that the EU battery production will be able to meet the domestic demand for BEV and PHEV passenger car vehicle batteries in the upcoming years. Initiatives such as EBA that connect stakeholders, as well as financial support from the EU for projects within the LIB industry, have accelerated the development of a local battery production industry.

With the rapid uptake of local battery producers in Europe, policy makers have increasing control over production standards and an easier access on information about environmental impacts. Battery designs are far from being standardized, impeding the work of recyclers and repurposers. Cell shapes vary between cylindrical, prismatic and pouch, and cell chemistries constantly change without the requirement of labelling, making it impossible for recyclers to identify the exact type of battery they are dealing with. A design for recycling or repurposing could increase the material recovery rates, reduce treatment costs and the environmental footprint. Currently, the EU Battery Directive does not require producers to label the batteries with their corresponding chemistry. Furthermore, LIB lifetime data of the BMS, which would give essential information for the repurposing process, is in the hands of the OEMs. A battery passport that contains vital lifetime data and information about the battery characteristics could solve these problems, increase the transparency, and facilitate both recycling and repurposing.

To support a better understanding of the battery technology and improve the accuracy of forecasts, further research on battery lifetime is needed and should be encouraged.

Recycling

The mining and refining of the raw materials showed the highest GHG emissions in the analysis, making recycling a keystone in the goal of reaching carbon neutrality. Essential for the amounts of material inside batteries that enter EOL are the number of vehicle registrations, the battery lifetime, and the battery sizes. All impact the EOL market and should therefore be tracked constantly and gathered in one database. This would allow precise forecasts of EOL battery volumes and give legislators the time and certainty to create regulatory measures that promote the circular battery value chain.

The scenario results suggested that by the mid-2020s, nickel and lithium will become the materials with the greatest economic importance for the recycling process. The current required EU LIB recovery rate of 50% by weight does not consider the different supply risks or environmental impacts of materials. Recyclers could thus decide to focus only on aluminium and graphite, which show the highest weight share within a NMC622 battery pack. Together with the plastics and steel this would account for roughly half of the weight while some of the materials with the highest import reliance such as cobalt and lithium would be lost. The recovery rate should therefore specify which materials are of special interest to the European LIB market and set high recovery targets for those materials. The list of materials should include nickel, lithium, copper, and cobalt. While graphite and manganese are of little economic interest, the import reliance is nevertheless high and could justify recovery rates for those materials as well.

Technological improvements of LIB design and chemistries will impact the recycling industry a decade later and therefore the speed in which political action is taken to improve sustainability of the LIB value chain, like fostering the design for recycling, should not be delayed.

To understand the environmental impacts of different recycling processes, a clear assessment methodology could be fixed to allow for fair comparison between different approaches. If standardization of battery design is achieved, automated disassembly could furthermore reduce time and cost of the dismantling steps in recycling plants. Together with the effects of economies of scale caused by the increasing numbers of EOL batteries the recycling could be profitable even if the cobalt contents are diminishing.

Second life

The scenario results indicated the great potential that second life batteries could have as cheap stationary storage solutions. They could be an essential component for storing intermittent renewable energy in times of low power demand or to stabilize the grid. Nevertheless, research on safety of second life applications is needed to market it in bigger numbers. Moreover, the liability for batteries during their second life must be clearly stated.

While the second battery life saves large emissions related to material mining and battery production, a second life delays the recycling process by several years and thus delays the inflow of recycled materials. In times of a strong market growth this increases the import dependency for the EU. Furthermore, with the uncertainty about the length of the second life, another variable is added that makes it more difficult to predict EOL volumes. However, once a stable rate of BEVs and PHEVs on the roads is reached, a circular flow of batteries with both reuse and recycling can be implemented.

A problem for a second life industry can be the unstable inflow of EOL batteries and the varying cell chemistries of different LIBs. A testing ground to overcome this problem could be public transport in cities. Cities could implement circular battery flows within their public bus systems. First, electric buses with identical battery types are implemented as low carbon means of transport. Second, once the batteries reach their EOL, the battery packs can be grouped together and used to support the local electricity grid. Third, after the second lifetime, the batteries are finally recycled, preferably locally, and the materials are fed back to the nearest LIB production facility. Thus, a circular economy for LIBs could be tested on a small scale, avoiding the uncontrolled loss of batteries in the free market, and providing results and valuable experiences for wider implementation.

5.7 Related work

Several scenario and material flow analyses have been conducted on the battery market in recent years. However, many of them either target different battery types, do not consider battery EOL, or cover only the Asian or North American market.

Articles were found that focus on the geopolitical side and analyze the supply risks of LIB materials, but concentrate on the virgin material demand for battery production without a strong emphasis on the potentials of recovering materials from EOL LIBs (Sun et al. 2019) (Olivetti et al. 2017). Other studies analyze different types of batteries such as lead acid batteries (Jeong and Kim 2018), or assess scenarios for the supply and demand of alternatives to LIBs such as sodium-ion batteries (Vaalma et al. 2018). Several studies are targeting specifically LIB materials, but several of those do not cover the EU market. A recent study on the material flow of LIB materials was conducted on the Chinese market, covering the time frame from 2000 to 2018 (Liu et al. 2021). One of the first publications that was connecting a material flow analysis to the potentials of second life of LIBs was conducted on the US market and published in 2014 as part of Kirti Richa's Doctor dissertation at the Rochester Institute of Technology (Richa et al. 2014). The analysis predicts LIB flows from 2015 to 2040 with 3 scenarios for several parameters such as EV sales and battery lifetime, where the latter was expressed as a truncated normal distribution to account for the variations in battery lifetime. Furthermore, the paper expresses the economic value of the materials in the EV LIB waste streams based on market spot prices. However, due to the very long projection period of 25 years and the uncertainties about the development of LIB chemistries, the results vary strongly. In 2018, (Ziemann et al. 2018) introduced time-based growing battery sizes and changing chemistries into their material flow analysis, and furthermore assessed whether recovered materials could be reused once again as EV batteries. Their analysis was performed on the global market and focused solely on lithium.

A recent study on the EU market was conducted by the EU Joint Research Institute (JRC) (Bobba et al. 2019). In this work, the authors develop an extensive material flow analysis to estimate the amount of material that will retire from EOL BEVs and PHEVs in the EU, and furthermore assess the benefits of different quotas for battery second life. The model also includes a sensitivity analysis of input values that determine the number of batteries entering the market. Results are calculated for the years 2005 to 2035, but solely the material flows of cobalt and lithium are presented, and no economic assessment is included. Their results show batteries available for second use application growing to 0,6 GWh of residual capacity by 2025 and varying between 2 and 13,5 GWh in 2030 for different repurposing scenarios. cobalt available for recycling varies between 3.000 and 5.000 tons in 2030, and the market demand for new batteries amounts to 34.000 tons in the same year, resulting in 9% to 15% of demand that could be met by recycled materials. Those results are similar to the values calculated in this thesis. However, batteries available for second life were found to be in a wider range due to the large scenario variations ranging from 20% to 60% reuse rates. Without considering any capacity fade, values were thus found to lay between 0,5 and 4,7 GWh for 2025 and 3,8 to 30,6 GWh. cobalt available for recycling in 2030 was found to vary between 2.320 and 5.851 tons when assuming a 100% collection rate, and cobalt demand for EV batteries was calculated demand of 33.829 tons in 2030. This results in 7% to 17% of cobalt demand that could theoretically be covered by recycled materials, and matching the results calculated by (Bobba et al. 2019).

6 Conclusion and future work

6.1 Conclusion

Predominantly lithium-based batteries are used to power passenger car electric vehicles due to favorable characteristics compared to other types of batteries (e.g. high energy density). However, compared to the more standardized designs of other batteries (e.g. lead acid batteries) LIBs vary strongly in cell shape (cylindrical, prismatic or pouch) and cell composition, impeding the standardization of EOL treatment. The trend towards using cathodes with higher nickel shares was detected, and LIBs using NMC622 cathodes were found to be the dominant type of chemistry when analyzing new BEV model launches in 2019. A more detailed analysis on weight distribution and raw materials inside LIBs was carried out, with a focus on 8 materials (aluminium, graphite, lithium, nickel, copper, steel, cobalt, manganese). On a per kg of material basis, cobalt showed by far the highest environmental impact, the highest costs and the highest supply risk for the EU. However, when normalizing the results to the quantities of materials within a NMC622 LIB, the results change. Aluminium becomes the material with the highest environmental impact due to the large quantities that are used, and nickel becomes the material with the highest economic importance. Thus, induced by the chemistry changes towards lower cobalt contents, the overall impact of cobalt on economics and environmental impact of LIBs is reducing. A discrepancy was detected for graphite, which shows the second highest supply risk out of the 8 materials, but only accounts for a small share of the battery material costs.

Global LIB manufacturing capacities are currently concentrated in Asia (China, South Korea), but several large-scale facilities are currently under construction in the EU. Prices for materials account for about half of the total cost per battery in a large production facility, and the environmental impact is driven by the high energy demand of the production process caused mainly by the drying process and running of the dry room.

The legislative framework around batteries in Europe is guided by several EU legislations centered around the EU Battery Directive. The legislation showed to be very unspecific regarding BEV and PHEV batteries. Within the EOL alternatives, only recycling is mentioned in the Battery Directive. Collection and recycling targets are low and not tailored to the materials inside LIBs. Many of the problems were identified in the evaluation study on the Battery Directive, and a new regulation is expected to be published in the upcoming months.

In the second part of the literature review, the EOL alternatives recycling and reuse of batteries were introduced. Reusing of LIBs showed to be still in the research phase, but many pilot projects were detected, and a variety of potential fields of application exist such as frequency stabilization for the grid or integration of intermittent renewable energy. While reusing saves emissions both from raw material mining and the energy intensive battery production, there is a lack of data on the environmental footprint of the repurposing process itself. Economically, repurposed batteries can be a cheap energy storage solution, but old generation second life batteries must compete with new batteries, which show falling prices and increased efficiencies. Furthermore, the safety of second life batteries is a topic of debate.

In contrast to the reuse of batteries, recycling is already a mature technology. As defined in the EU Battery Directive, all batteries must undergo a recycling treatment, for which different technologies exist. Pyrometallurgy is the simplest process since it requires little pretreatment, but also produces the highest GHG emissions and traditional processes fail to recover lithium, aluminium and manganese which end up in the slag (the process works well for the recovery of nickel, cobalt and copper). Hydrometallurgy is based on leaching and shows high recovery rates, also for lithium. Drawbacks were found in the prerequisite of complex pretreatment, such as discharge and disassembly of modules. Direct cathode recycling is a novel approach, which recovers the entire cathode and thus avoids the manufacturing of new cathodes from the raw materials. However, this process is still in a research stage and it is unclear whether the process can be successfully implemented while battery chemistries are undergoing constant changes.

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.

Recyclers should have to fulfill ambitious recovery rates for the essential materials inside LIBs: nickel, lithium, cobalt and copper (materials with highest economic impact), and furthermore aluminium, manganese (high environmental impact) and graphite (high EU supply risk).

To optimize the European LIB value chain towards circularity, a clear regulatory framework regarding second life and recycling must be implemented. Current legislations fail to specify LIB as a separate battery type and do not mention the reuse of batteries. Furthermore, more standardized battery designs and transparent access to data on battery characteristics and cycling behavior would favor a circular economy.

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.

6.2 Future work

The global battery market for electric vehicles is constantly transforming and technological improvements can rapidly disrupt the industry. This study focused on LIBs as the current industry standard, but the future could show a shift towards novel battery types such as solid-state batteries. Further studies can follow the same approach as presented in this thesis but must consider the innovations in battery technologies and assess their implications for the EOL sector. A shift in material composition could heavily alter the economics of the recycling industry.

To expand the scenario analysis, electric vehicles other than passenger car BEVs and PHEVs can be studied. While today numbers are still negligibly low, electric buses or trucks carry batteries with much larger capacities than passenger cars and thus could become a major factor for the EOL industry.

Moreover, the analysis could further be refined by improving the input data and reducing the limitations that were listed in chapter 4. Especially the environmental assessment was found to show great levels of uncertainty and data quality and standardization of the assessment can be improved. Transport can be added as another refinement of the results, even though the impact is expected to be small. The lifetime of batteries showed to be a critical factor for the entire EOL industry, and further research is needed to improve the understanding of battery aging.

While electric vehicles are seeing a rapid uptake and receive much media attention, they should constantly be compared to other means of transport. For reaching a circular economy in the EU transport sector, other potentially carbon free technologies such as hydrogen powered fuel cell cars must be assessed alongside electric vehicles. Furthermore, the focus should not only be about efficiency, but also about sufficiency. Increasing recycling rates and fostering the reuse of batteries promise environmental benefits, but a much stronger impact will come from a reduction of the number of vehicles on the road and a reduction in vehicle sizes.

7 Publication bibliography

ACEA (2020): Key Figures | ACEA - European Automobile Manufacturers' Association. Available online at https://theicct.org/sites/default/files/publications/European_vehicle_market_statistics_20192020_20191216.pdf, updated on 6/9/2020.000Z, checked on 6/9/2020.

Ager-Wick Ellingsen, Linda; Hung, Christine Roxanne (2018): Research for TRAN Committee - Battery-powered electric vehicles: market development and lifecycle emissions STUDY. Edited by European Union.

Ahmadi, Leila; Yip, Arthur; Fowler, Michael; Young, Steven B.; Fraser, Roydon A. (2014): Environmental feasibility of re-use of electric vehicle batteries. In *Sustainable Energy Technologies and Assessments* 6, pp. 64–74. DOI: 10.1016/j.seta.2014.01.006.

Assunção, André; Moura, Pedro S.; Almeida, Aníbal T. de (2016): Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy. In *Applied Energy* 181, pp. 120–131. DOI: 10.1016/j.apenergy.2016.08.056.

Audi (2019): Audi eröffnet Batteriespeicher auf Berliner EUREF-Campus. Available online at https://www.audi-mediacenter.com/de/pressemitteilungen/audi-eroeffnet-batteriespeicher-auf-berliner-euref-campus-11681, updated on 8/5/2020, checked on 8/5/2020.

Banza Lubaba Nkulu, Célestin; Casas, Lidia; Haufroid, Vincent; Putter, Thierry de; Saenen, Nelly D.; Kayembe-Kitenge, Tony et al. (2018): Sustainability of artisanal mining of cobalt in DR Congo. In *Nature sustainability* 1 (9), pp. 495–504. DOI: 10.1038/s41893-018-0139-4.

Baranzelli, Claudia; Blagoeva, Darina; Blengini, Gian Andrea; Ciupagea, Constantin; Dewulf, Jo; Dias, Patricia et al. (2017): Methodology for establishing the EU list of critical raw materials. Guidelines. Luxembourg: Publications Office of the European Union.

Blagoeva, D.; Pavel, C.; Wittmer, D.; Huisman, J.; Pasimeni, F. (2019): Materials dependencies for dual-use technologies relevant for Europe's defence sector. Luxembourg: Publications Office of the European Union (EUR, 29850).

Blanpain, Bart; Arnout, Sander; Chintinne, Mathias; R. Swinbourne, Douglas (2014): Lead Recycling. In Ernst Worrell, Markus A. Reuter (Eds.): Handbook of recycling. State-of-the-art for practitioners, analysts, and scientists. Amsterdam, Boston, Heidelberg, London, New York, Oxford, Paris, San Diego, San Francisco, Sydney, Tokyo: Elsevier, pp. 95–111.

BMW (2020): BMW i Battery Certificate - German Version - SA7AQ. Available online at https://www.bmw.de/content/dam/bmw/marketDE/bmw_de/topics/offers-and-services/warranty/pdf/BMWi-Battery-Certificate.pdf.asset.1490193447915.pdf, checked on 6/17/2020.

Bobba, Silvia; Mathieux, Fabrice; Ardente, Fulvio; Blengini, Gian Andrea; Cusenza, Maria Anna; Podias, Andreas; Pfrang, Andreas (2018a): Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. In *Journal of Energy Storage* 19, pp. 213–225. DOI: 10.1016/j.est.2018.07.008.

Bobba, Silvia; Mathieux, Fabrice; Blengini, Gian Andrea (2019): How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. In *Resources, Conservation and Recycling* 145, pp. 279–291. DOI: 10.1016/j.resconrec.2019.02.022.

Bobba, Silvia; Podias, Andreas; Di Persio, Franco; Messagie, Maarten; Tecchio, Paolo; Cusenza, Maria Anna et al. (2018b): Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB). Edited by European Commission (JRC).

Bonell, Marta; Carrillo, Viviana; Chanson, Claude; Ebert, Thomas; Gediga, Johannes; Mistry, Mark et al. (2018): PEFCR. Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications. Version H. Edited by Recharge, checked on 5/24/2020.

Boxall, Naomi J.; King, Sarah; Cheng, Ka Yu; Gumulya, Yosephine; Bruckard, Warren; Kaksonen, Anna H. (2018): Urban mining of lithium-ion batteries in Australia: Current state and future trends. In *Minerals Engineering* 128, pp. 45–55. DOI: 10.1016/j.mineng.2018.08.030.

Chen, Mengyuan; Ma, Xiaotu; Chen, Bin; Arsenault, Renata; Karlson, Peter; Simon, Nakia; Wang, Yan (2019): Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries. In *Joule* 3 (11), pp. 2622–2646. DOI: 10.1016/j.joule.2019.09.014.

Cheret, Daniel; Santen, Sven (2007): Battery recycling. Patent no. US 7,169,206 B2.

Ciez, Rebecca E.; Whitacre, J. F. (2019): Examining different recycling processes for lithium-ion batteries. In *Nature sustainability* 2 (2), pp. 148–156. DOI: 10.1038/s41893-019-0222-5.

CleanTechnica (2019): Energy Storage News: CATL Factory In Germany & Rio Tinto's Lithium Plant In California | CleanTechnica. Available online at https://cleantechnica.com/2019/10/22/energy-storage-news-catl-factory-in-germany-rio-tintos-lithium-plant-in-california/, updated on 10/23/2019+00:00, checked on 6/3/2020.

CleanTechnica (2020): Elon Musk Shares History Of Tesla Battery Modules & Why They Are Going Away | CleanTechnica. Available online at https://cleantechnica.com/2020/02/02/elon-musk-shares-history-of-tesla-battery-modules-why-they-are-going-away/, updated on 2/2/2020+00:00, checked on 5/18/2020.

Clements, Sarah; Ruf, Lisa (2020): UK Energy Storage Lab Projects (UKESL). Public Report. Edited by UK Department for Business, Energy & Industrial Strategy, University of Warwick, Nissan, Ametek, elementenergy. Available online at http://www.element-energy.co.uk/wordpress/wp-content/uploads/2020/01/UKESL-Non-technical-Public-Report_2020.pdf.

Connected Energy (2020): Advanced Energy Storage Solutions. Available online at https://www.c-e-int.com/technology/e-stor-overview/, updated on 8/5/2020, checked on 8/5/2020.

Dai, Q.; Winjobi O. (2019): Updates for Battery Recycling and Materials in GREET 2019. Edited by Argonne National Laboratory. Available online at https://greet.es.anl.gov/publication-battery_recycling_materials_2019.

Dai, Qiang; Spangenberger, Jeffrey; Ahmed, Shabbir; Gaines, Linda; Kelly, Jarod C.; Wang, Michael (2019): EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model. Edited by Argonne National Laboratory.

Daimler (2016): World's largest 2nd-use battery storage is starting up. Available online at https://media.daimler.com/marsMediaSite/en/instance/ko.xhtml?oid=13634457, updated on 8/4/2020, checked on 8/4/2020.

Dang, Hui; Wang, Benfeng; Chang, Zhidong; Wu, Xue; Feng, Jingge; Zhou, Hualei et al. (2018): Recycled Lithium from Simulated Pyrometallurgical Slag by Chlorination Roasting. In *ACS Sustainable Chem. Eng.* 6 (10), pp. 13160–13167. DOI: 10.1021/acssuschemeng.8b02713.

Davidsson Kurland, Simon (2020): Energy use for GWh-scale lithium-ion battery production. In *Environ. Res. Commun.* 2 (1), p. 12001. DOI: 10.1088/2515-7620/ab5e1e.

DERA (2020): Preismonitor Rohstoffe. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). Available online at https://www.deutsche-rohstoffagentur.de/DERA/DE/Rohstoffinformationen/Rohstoffpreise/Preismonitor/preismonitor_node.html.

Diekerhof, Michael; Nouti, Diala; Pitz, Manuel; Wirtz, Nikolaus (2018): Energy Local Storage Advanced system - Technical impact analysis and proof-of-concept on system level. WP6 - Design optimization and technical impact analysis. Edited by Energy Local Storage Advanced system (ELSA).

Diekmann, Jan; Hanisch, Christian; Froböse, Linus; Schälicke, Gerrit; Loellhoeffel, Thomas; Fölster, Anne-Sophie; Kwade, Arno (2017): Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes. In *J. Electrochem. Soc.* 164 (1), A6184-A6191. DOI: 10.1149/2.0271701jes.

Duesenfeld (2020a): Managing processes safely with a patented method - Duesenfeld. Available online at https://www.duesenfeld.com/safety.html, updated on 7/10/2020.000Z, checked on 7/10/2020.

Duesenfeld (2020b): 4,8 t CO2-Einsparung pro Tonne recycelter Batterien. Available online at https://www.duesenfeld.com/recycling.html, updated on 7/31/2020, checked on 7/31/2020.

Duesenfeld (2020c): Mobile Recyclingcontainer reduzieren Gefahrguttransporte. Available online at https://www.duesenfeld.com/mobil.html, updated on 7/31/2020, checked on 7/31/2020.

Dunn, J. B.; Gaines, L.; Barnes, M.; Sullivan, J.; Wang, M. (2014): Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle. Edited by Argonne National Laboratory. US Department of Energy.

Duong, Hieu; Shin, Joon; Yudi, Yudi (2018): Dry Electrode Coating Technology. Edited by Maxwell Technologies. San Diego. Available online at https://www.semanticscholar.org/paper/Dry-Electrode-Coating-Technology-Duong-Shin/f5e882e125a1579b2b3cca88ed512c47fdcefcc0.

EAFO (2020a): Passenger cars | EAFO. Available online at https://www.eafo.eu/vehicles-and-fleet/m1, updated on 6/9/2020.000Z, checked on 6/9/2020.

EAFO (2020b): Vehicles and fleet. Edited by European Alternative Fuels Observatory (EAFO). Available online at https://www.eafo.eu/vehicles-and-fleet, updated on 7/12/2020, checked on 12/7/2020.

Eduljee, G. H.; Harrison, R. M. (Eds.) (2019): Electronic Waste Management. Cambridge: Royal Society of Chemistry (Issues in Environmental Science and Technology).

EIB (2020): Electric vehicle battery production in Europe gets boost thanks to EIB loan of €480 million to LG Chem Wroclaw Energy in Poland. Edited by European Investment Bank (EIF). Available online at https://www.eib.org/en/press/all/2020-088-electric-vehicle-battery-production-in-europe-gets-boost-thanks-to-eib-loan-of-eur480-million-to-lg-chem-wroclaw-energy-in-poland, updated on 6/3/2020.000Z, checked on 6/3/2020.

Electrive (2018): Renault to install Europe's largest 2nd life battery storage - electrive.com. Available online at https://www.electrive.com/2018/09/26/renault-to-install-europes-largest-2nd-life-battery-storage/, updated on 2/8/2019, checked on 8/5/2020.

Ellingsen, Linda Ager-Wick; Majeau-Bettez, Guillaume; Singh, Bhawna; Srivastava, Akhilesh Kumar; Valøen, Lars Ole; Strømman, Anders Hammer (2014): Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. In *Journal of Industrial Ecology* 18 (1), pp. 113–124. DOI: 10.1111/jiec.12072.

Erik Emilsson, Lisbeth Dahllöf (2019): Lithium-Ion Vehicle Battery Production. Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling. Edited by IVL Swedish Energy Agency, checked on 6/8/2020.

European Commission (2005): Commission Decision of 1 April 2005 laying down detailed rules on the monitoring of the European Parliament and of the Council on end-of-life vehicles. 2005/293/EC. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32005D0293&from=EN, checked on 6/22/2020.

European Commission (2006): DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCILof 6 September 2006on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. Battery Directive. Source: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006L0066-20131230&rid=1. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006L0066-20131230&rid=1, checked on 6/30/2020.

European Commission (Ed.) (2010): Product Environmental Footprint (PEF) Guide. Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006L0066-20131230&rid=1, checked on 6/28/2020.

European Commission (2017a): Study on the review of the list of critical raw materials. Critical raw materials factsheets. Luxembourg: Publications Office of the European Union.

European Commission (2017b): Study on the review of the list of critical raw materials. Non-critical raw materials factsheets. Luxembourg: Publications Office of the European Union.

European Commission (2018): The world’s greenest battery - investEU - European Commission. Available online at https://europa.eu/investeu/projects/world%E2%80%99s-greenest-battery_en, updated on 4/16/2019, checked on 9/17/2020.

European Commission (2019a): Commission Staff Working Document. on the evaluation of the Directive 2006/66/EV on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. Available online at https://ec.europa.eu/environment/waste/batteries/pdf/evaluation_report_batteries_directive.pdf, checked on 6/10/2020.

European Commission (2019b): Energy Local Storage Advanced system (ELSA). Publication Office/CORDIS. Available online at https://cordis.europa.eu/project/id/646125/de, updated on 7/30/2020, checked on 4/8/2020.

European Commission (2019c): Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. on the implementation and the impact on the environment and the functioning of the internal market of Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. Brussels.

European Commission (2019d): The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Available online at https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, checked on 3/3/2020.

European Commission (2020): European Battery Alliance - Internal Market, Industry, Entrepreneurship and SMEs - European Commission. Available online at https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en, updated on 5/8/2018+02:00, checked on 6/10/2020.

European Environment Agency (2020): Monitoring of CO2 emissions from passenger cars. Available online at http://co2cars.apps.eea.europa.eu, updated on 7/12/2020, checked on 12/7/2020.

European Parliament (2019): Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. Regulation (EU) 2019/631. In *Official Journal of the European Union* (Volume 62). Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2019:111:TOC.

Eurostat (2016): Passenger car - Statistics Explained. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Passenger_car, updated on 7/12/2020, checked on 12/7/2020.

Eurostat (2019): Energy balance sheets. 2017 data: 2019 edition. Luxembourg: Publications Office of the European Union (Energy balance sheets, 2017 data, 2019).

EWEA (2020): Wind energy frequently asked questions (FAQ)| EWEA. Available online at https://www.ewea.org/wind-energy-basics/faq/, updated on 9/6/2020, checked on 9/6/2020.

Eynard, Umberto; Georgitzikis, Konstantinos; Wittmer, Dominic; EL Latunussa, Cynthia; Torres de Matos, Cristina; Mancini, Lucia et al. (2020a): Study on the EU's list of Critical Raw Materials. Critical Raw Materials Factsheets. Edited by European Commission.

Eynard, Umberto; Georgitzikis, Konstantinos; Wittmer, Dominic; EL Latunussa, Cynthia; Torres de Matos, Cristina; Mancini, Lucia et al. (2020b): Study on the EU's list of Critical Raw Materials. Non-Critical Raw Materials Factsheets. Edited by European Commission.

Fan, Ersha; Li, Li; Wang, Zhenpo; Lin, Jiao; Huang, Yongxin; Yao, Ying et al. (2020): Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. In *Chemical reviews* 120 (14), pp. 7020–7063. DOI: 10.1021/acs.chemrev.9b00535.

Flexer, Victoria; Baspineiro, Celso Fernando; Galli, Claudia Inés (2018): Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. In *The Science of the total environment* 639, pp. 1188–1204. DOI: 10.1016/j.scitotenv.2018.05.223.

Foster, Meaghan; Isely, Paul; Standridge, Charles Robert; Hasan, Md Mehedi (2014): Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. In *JIEM* 7 (3). DOI: 10.3926/jiem.939.

Foudraz, Jean-Claude; Farouk, Tedjar (2007): Method for the mixed recycling of lithium-based anode batteries and cells. Patent no. US2007196725A1.

Frank Treffer (2017): Industrial scale EOL (X)EV Battery Recycling –an existing solution in a global network, 2017. Available online at https://www.deutscher-rohstoffeffizienz-preis.de/DERA/DE/Aktuelles/rohstoff_lithium.html.

Gaines, Linda (2014): The future of automotive lithium-ion battery recycling: Charting a sustainable course. In *Sustainable Materials and Technologies* 1-2, pp. 2–7. DOI: 10.1016/j.susmat.2014.10.001.

Gaines, Linda (2018a): Lithium-ion battery recycling processes: Research towards a sustainable course. In *Sustainable Materials and Technologies* 17, e00068. DOI: 10.1016/j.susmat.2018.e00068.

Gaines, Linda (2019): Profitable Recycling of Low-Cobalt Lithium-Ion Batteries Will Depend on New Process Developments. In *One Earth* 1 (4), pp. 413–415. DOI: 10.1016/j.oneear.2019.12.001.

Gaines, Linda; Richa, Kirti; Spangenberger, Jeffrey (2018b): Key issues for Li-ion battery recycling. In *MRS energy sustain.* 5. DOI: 10.1557/mre.2018.13.

Gaines, Linda; Sullivan, John; Burnham, Andrew (2010): Paper No. 11-3891 Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling. Submitted August 1, 2010 for presentation at and inclusion in the compact disc of the 90th Annual Meeting of the Transportation Research Board, Washington, D.C. Available online at https://www.researchgate.net/publication/265158823_Paper_No_11-3891_Life-Cycle_Analysis_for_Lithium-Ion_Battery_Production_and_Recycling, checked on 6/24/2020.

Gautam, Meenu; Pandey, Bhanu; Agrawal, Madhoolika (2018): Carbon Footprint of Aluminum Production. In Subramanian Senthilkannan Muthu (Ed.): Environmental carbon footprints. Industrial case studies. Kidlington, Oxford, United Kingdom: Butterworth-Heinemann an imprint of Elsevier, pp. 197–228.

Gennaro, Michele de; Paffumi, Elena; Martini, Giorgio; Giallonardo, Andrew; Pedroso, Samuel; Loiselle-Lapointe, Aaron (2020): A case study to predict the capacity fade of the battery of electrified vehicles in real-world use conditions. In *Case Studies on Transport Policy* 8 (2), pp. 517–534. DOI: 10.1016/j.cstp.2019.11.005.

Gohla-Neudecker, B.; Maiyappan, V. S.; Juraschek, S.; Mohr, S. (2017): Battery 2nd life: Presenting a benchmark stationary storage system as enabler for the global energy transition. In : Renewable energy resources impact. 2017 6th International Conference on Clean Electrical Power (ICCEP) : Santa Margherita Ligure, 27-29 June 2017. 2017 6th International Conference on Clean Electrical Power (ICCEP). Santa Margherita Ligure, Italy, 6/27/2017 - 6/29/2017. International Conference on Clean Electrical Power; Institute of Electrical and Electronics Engineers; ICCEP. Piscataway, NJ: IEEE, pp. 103–109.

GreenDelta GmbH (2020): openLCA Nexus: PEF database. ecoinvent Production of Chemicals Datasets created in the context of the Environmental Footprint (EF). Edited by Ecoinvent. Available online at https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf, updated on 2020, checked on 5/23/2020.

Groupe Renault (2019): Black Swan, the first 100% electric passenger boat fitted with second life batteries comes to Paris. Available online at https://en.media.groupe.renault.com/news/black-swan-the-first-100-electric-passenger-boat-fitted-with-second-life-batteries-comes-to-paris-dda5-989c5.html, updated on 8/4/2020, checked on 8/4/2020.

Groupe Renault (2020): A second life for batteries: from energy usage to industrial storage. Available online at https://easyelectriclife.groupe.renault.com/en/outlook/a-second-life-for-batteries-from-energy-usage-to-industrial-storage/, updated on 6/3/2020, checked on 8/5/2020.

Hall, Dale; Lutsey, Nic (2018): Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions. With assistance of Dale Hall, Nic Lutsey. The International Council on Clean Transportation (ICCT). Available online at https://www-nature-com.focus.lib.kth.se/articles/s41893-018-0139-4.pdf, checked on 3/3/2020.

Hanisch, Christian; Diekmann, Jan; Stieger, Alexander; Haselrieder, Wolfgang; Kwade, Arno (2015): Recycling of Lithium-Ion Batteries. In Jinyue Yan (Ed.): Handbook of Clean Energy Systems. Weinheim: Wiley, pp. 1–24.

Harlow, Jessie E.; Ma, Xiaowei; Li, Jing; Logan, Eric; Liu, Yulong; Zhang, Ning et al. (2019): A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies. In *J. Electrochem. Soc.* 166 (13), A3031-A3044. DOI: 10.1149/2.0981913jes.

Harper, Gavin; Sommerville, Roberto; Kendrick, Emma; Driscoll, Laura; Slater, Peter; Stolkin, Rustam et al. (2019): Recycling lithium-ion batteries from electric vehicles. In *Nature* 575 (7781), pp. 75–86. DOI: 10.1038/s41586-019-1682-5.

Hettesheimer, Tim (2017): Strategische Produktionsplanung in jungen Märkten. Dissertation. Fraunhofer-Institut für System- und Innovationsforschung; Fraunhofer IRB-Verlag.

Hossain, Eklas; Murtaugh, Darren; Mody, Jaisen; Faruque, Hossain Mansur Resalat; Haque Sunny, Md. Samiul; Mohammad, Naeem (2019): A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies. In *IEEE Access* 7, pp. 73215–73252. DOI: 10.1109/ACCESS.2019.2917859.

Huang, Bin; Pan, Zhefei; Su, Xiangyu; An, Liang (2018): Recycling of lithium-ion batteries: Recent advances and perspectives. In *Journal of Power Sources* 399, pp. 274–286. DOI: 10.1016/j.jpowsour.2018.07.116.

Huisman, J.; Ciuta, T.; Mathieux, F.; Bobba, S.; Georgitzikis, K.; Pennington D. (2020): RMIS - Raw Materials in the Battery Value Chain. Final content for the Raw Materials Information System - strategic value chain - batteries section. Edited by European Commission (JRC). Available online at https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf, checked on 5/4/2020.

ICCT (2019): European vehicle market statistics: Pocketbook 2019-2020. Edited by The International Council on Clean Transportation (ICCT), checked on 6/9/2020.

ICCT (2020a): European vehicle market statistics, 2017/2018 | International Council on Clean Transportation. Available online at https://theicct.org/publications/european-vehicle-market-statistics-20172018, updated on 9/13/2020, checked on 9/13/2020.

ICCT (2020b): European vehicle market statistics, 2018/2019 | International Council on Clean Transportation. Available online at https://theicct.org/publications/european-vehicle-market-statistics-20182019, updated on 9/13/2020, checked on 9/13/2020.

ICCT (2020c): European vehicle market statistics, 2019/2020 | International Council on Clean Transportation. Available online at https://theicct.org/publications/european-vehicle-market-statistics-20192020, updated on 9/13/2020, checked on 9/13/2020.

InvestmentMine (2020): Cobalt Prices and Cobalt Price Charts. Available online at http://www.infomine.com/investment/metal-prices/cobalt/, updated on 7/6/2020.000Z, checked on 7/6/2020.

Jana, Aniruddha; Shaver, Gregory M.; García, R. Edwin (2019): Physical, on the fly, capacity degradation prediction of LiNiMnCoO2-graphite cells. In *Journal of Power Sources* 422, pp. 185–195. DOI: 10.1016/j.jpowsour.2019.02.073.

Jeong, Kwang-Pil; Kim, Jeong Gon (2018): Lead acid battery recycling and material flow analysis of lead in Korea. In *J Mater Cycles Waste Manag* 20 (2), pp. 1348–1354. DOI: 10.1007/s10163-017-0649-6.

Joulié, M.; Billy, E.; Laucournet, R.; Meyer, D. (2017): Current collectors as reducing agent to dissolve active materials of positive electrodes from Li-ion battery wastes. In *Hydrometallurgy* 169, pp. 426–432. DOI: 10.1016/j.hydromet.2017.02.010.

Jow, T. Richard; Xu, Kang; Borodin, Oleg; Ue, Makoto (Eds.) (2014): Electrolytes for Lithium and Lithium-Ion Batteries. New York, NY, s.l.: Springer New York (Modern Aspects of Electrochemistry, 58). Available online at http://gbv.eblib.com/patron/FullRecord.aspx?p=1730876.

Julien, Christian; Mauger, Alain; Vijh, Ashok; Zaghib, Karim (2016): Lithium Batteries. Science and Technology. Cham: Springer. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32005D0293&from=EN, checked on 4/22/2020.

KBA (2020): Kraftfahrt-Bundesamt - Fahrzeugzulassungen - Pressemitteilung Nr. 01/2020 - Fahrzeugzulassungen im Dezember 2019 - Jahresbilanz - korrigierte Fassung. Available online at https://www.kba.de/DE/Presse/Pressemitteilungen/2020/Fahrzeugzulassungen/pm01_2020_n_12_19_pm_komplett.html?nn=2562684, updated on 3/3/2020, checked on 3/3/2020.

Kurzweil, Peter (2015): Lithium Battery Energy Storage. In Patrick T. Moseley, Jürgen Garche, Peter Adelmann (Eds.): Electrochemical energy storage for renewable sources and grid balancing. Amsterdam, Netherlands: Elsevier, pp. 269–307.

Lacey, Gillian; Putrus, Ghamin; Salim, Anwar (2013): The use of second life electric vehicle batteries for grid support. In : Eurocon 2013. IEEE EUROCON 2013. Zagreb, Croatia, 01.07.2013 - 04.07.2013: IEEE, pp. 1255–1261.

Lai, Yan-Qing; Xu, Ming; Zhang, Zhi-An; Gao, Chun-Hui; Wang, Peng; Yu, Zi-Yang (2016): Optimized structure stability and electrochemical performance of LiNi0.8Co0.15Al0.05O2 by sputtering nanoscale ZnO film. In *Journal of Power Sources* 309, pp. 20–26. DOI: 10.1016/j.jpowsour.2016.01.079.

Larouche, François; Tedjar, Farouk; Amouzegar, Kamyab; Houlachi, Georges; Bouchard, Patrick; Demopoulos, George P.; Zaghib, Karim (2020): Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. In *Materials (Basel, Switzerland)* 13 (3). DOI: 10.3390/ma13030801.

Lebedeva, N.; Tarvydas, D.; Tsiropoulos, I. (2018): Li-ion batteries for mobility and stationary storage applications. Scenarios for costs and market growth. Luxembourg: Publications Office of the European Union (EUR, Scientific and technical research series, 29440).

Li, Matthew; Lu, Jun (2020): Cobalt in lithium-ion batteries. In *Science (New York, N.Y.)* 367 (6481), pp. 979–980. DOI: 10.1126/science.aba9168.

Li, Matthew; Lu, Jun; Chen, Zhongwei; Amine, Khalil (2018): 30 Years of Lithium-Ion Batteries. In *Advanced materials (Deerfield Beach, Fla.)*, e1800561. DOI: 10.1002/adma.201800561.

Liu, Wenqiu; Liu, Wei; Li, Xinxin; Liu, Yeye; Ogunmoroti, Abiodun Emmanuel; Li, Muyang et al. (2021): Dynamic material flow analysis of critical metals for lithium-ion battery system in China from 2000–2018. In *Resources, Conservation and Recycling* 164, p. 105122. DOI: 10.1016/j.resconrec.2020.105122.

LME (2020): Historical data for cash settled futures. Edited by London Metal Exchange (LME). Available online at https://www.deutsche-rohstoffagentur.de/DERA/DE/Aktuelles/Monitore/04-20/2020-04-preismonitor.pdf;jsessionid=A0FB73A3D44B562FABCE9C8EBDF9FD64.1_cid284?__blob=publicationFile&v=2, updated on 5/23/2020.000Z, checked on 5/23/2020.

Lutsey, Nic; Nicholas, Michael (2019): Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. Edited by The International Council on Clean Transportation (ICCT).

National Renewable Energy Laboratory (2020): Repurposing Cost Calculator: Alliance for Sustainable Energy of the U.S. Department of Energy.

Nelson, Paul; Ahmed, Shabbir; Gallagher, Kevin; Dees, Dennis; Kubal, Joseph; Song, Juhyun; Robertson, David (2019): BatPaC (Battery Performance and Cost). Version 4.0: Argonne National Laboratory. Available online at https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/2019_08_16_Task%204_Technologies_final.pdf.

Neubauer, J.; Smith, K.; Wood, E.; Pesaran, A. (2015a): Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries. Edited by National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy.

Neubauer, Jeremy S.; Wood, Eric; Pesaran, Ahmad (2015b): A Second Life for Electric Vehicle Batteries: Answering Questions on Battery Degradation and Value. In *SAE Int. J. Mater. Manf.* 8 (2), pp. 544–553. DOI: 10.4271/2015-01-1306.

OFV (2020): Bilsalget i 2019 – Opplysningsrådet for veitrafikken. Available online at https://ofv.no/bilsalget/bilsalget-i-2019, updated on 3/3/2020, checked on 3/3/2020.

Oh, Jimin; Kim, Jumi; Lee, Yong Min; Shin, Dong Ok; Kim, Ju Young; Lee, Young-Gi; Kim, Kwang Man (2019): High-rate cycling performance and surface analysis of LiNi1-Co/2Mn/2O2 (x=2/3, 0.4, 0.2) cathode materials. In *Materials Chemistry and Physics* 222, pp. 1–10. DOI: 10.1016/j.matchemphys.2018.09.076.

Olivetti, Elsa A.; Ceder, Gerbrand; Gaustad, Gabrielle G.; Fu, Xinkai (2017): Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. In *Joule* 1 (2), pp. 229–243. DOI: 10.1016/j.joule.2017.08.019.

openLCA Nexus (2020): openLCA Nexus: The source for LCA data sets. Available online at https://nexus.openlca.org/databases, updated on 7/31/2020, checked on 9/14/2020.

Peters, Jens F.; Weil, Marcel (2018): Providing a common base for life cycle assessments of Li-Ion batteries. In *Journal of Cleaner Production* 171, pp. 704–713. DOI: 10.1016/j.jclepro.2017.10.016.

Pistoia, Gianfranco; Liaw, Boryann (2018): Behaviour of Lithium-Ion Batteries in Electric Vehicles. Cham: Springer International Publishing.

Powervault (2017): Powervault and Renault give EV Batteries a "Second-Life" in Smart Energy Deal - Powervault. Available online at https://www.powervault.co.uk/article/powervault-and-renault-give-ev-batteries-a-second-life-in-smart-energy-deal/, updated on 8/5/2020, checked on 8/5/2020.

Powervault (2020): Build the Powervault you need for your home. Available online at https://www.powervault.co.uk/choose-your-powervault/, updated on 8/5/2020, checked on 8/5/2020.

Press Office Saxony-Anhalt (2019): Pressemitteilung Nr.: 043/2019. Edited by Ministerium für Wirtschaft, Wissenschaft und Digitalisierung. Available online at http://www.presse.sachsen-anhalt.de/index.php?&cmd=get&id=902900&identifier=c10f4a427047606887ab5e99a6f491a3, updated on 6/3/2020.000Z, checked on 6/3/2020.

Recanati, Francesca; Ciroth, Andreas (2019): Product Environmental Footprints. Secondary data in openLCA. Edited by GreenDelta GmbH. Available online at https://nexus.openlca.org/database/Environmental%20Footprints.

Reid, Gerard; Julve, Javier (2016): Second Life-Batteries As Flexible Storage For Renewable Energies. Edited by Bundesverband Erneuerbare Energie e.v. (BEE), Hannover Messe.

Richa, Kirti (2016): Sustainable management of lithium-ion batteries after use in electric vehicles. Dissertation. Rochester Institute of Technology. Department of Sustainability.

Richa, Kirti; Babbitt, Callie W.; Gaustad, Gabrielle; Wang, Xue (2014): A future perspective on lithium-ion battery waste flows from electric vehicles. In *Resources, Conservation and Recycling* 83, pp. 63–76. DOI: 10.1016/j.resconrec.2013.11.008.

Schwartz, Peter (2005): The art of the long view. Planning for the future in an uncertain world. Reprinted. Chichester: Wiley & Sons.

Shi, Yang; Chen, Gen; Liu, Fang; Yue, Xiujun; Chen, Zheng (2018): Resolving the Compositional and Structural Defects of Degraded LiNi x Co y Mn z O 2 Particles to Directly Regenerate High-Performance Lithium-Ion Battery Cathodes. In *ACS Energy Lett.* 3 (7), pp. 1683–1692. DOI: 10.1021/acsenergylett.8b00833.

Sun, Xin; Hao, Han; Hartmann, Philipp; Liu, Zongwei; Zhao, Fuquan (2019): Supply risks of lithium-ion battery materials: An entire supply chain estimation. In *Materials Today Energy* 14, p. 100347. DOI: 10.1016/j.mtener.2019.100347.

Takeshita et al. (2016): LIB Cell Materials Market Bulletin (16Q1). Edited by B3 Corporation.

Takeshita et al. (2018): LIB Materials Market Bulletin (18Q1). Edited by B3 Corporation.

Takeshita et al. (2019): LIB-equipped Vehicle Market Bulletin (19Q4) and Long-term LIB Market Forecast. Edited by B3 Corporation.

Tesla (2020): Vehicle Warranty. Battery warranty period. Available online at https://www.tesla.com/support/vehicle-warranty?redirect=no, updated on 2/10/2020-08:00, checked on 6/17/2020.

The Mobility House (2018a): 3 Megawatt Energiespeicher in der Johan Cruijff ArenA ist am Netz. Available online at https://www.mobilityhouse.com/de_de/magazin/pressemeldungen/johan-cruijff-arena-3mw-energiespeicher-am-netz.html, updated on 8/5/2020, checked on 8/5/2020.

The Mobility House (2018b): Elverlingsen: Ein Kohlekraftwerk wird zum automobilen Batteriespeicher. Available online at https://www.mobilityhouse.com/de_de/magazin/pressemeldungen/batteriespeicher-elverlingsen.html, updated on 8/4/2020, checked on 8/4/2020.

The Mobility House (2019): Demeter investiert in Second-Life Batterieprojekt der Renault-Gruppe und The Mobility House. Available online at https://www.mobilityhouse.com/de_de/magazin/pressemeldungen/demeter-projektgesellschaft.html, updated on 8/5/2020, checked on 8/5/2020.

Thielmann, Axel; Neef, Christoph; Hettesheimer, Tim; Döscher, Henning; Wietschel, Martin; Tübke, Jens (2017): Energiespeicher-Roadmap_Update 2017. Hochenergie-Batterien 2030+ und Perspektiven zukünftige Batterietechnologien. Edited by Fraunhofer ISI.

Thielmann, Axel; Wietschel, Martin; Funke, Simon; Grimm, Anna; Hettesheimer, Tim; Langkau, Sabine et al. (2020): Batterien für Elektroautos: Faktencheck und Handlungsbedarf. Edited by Fraunhofer ISI. Karlsruhe. Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2020/Faktencheck-Batterien-fuer-E-Autos.pdf, checked on 4/20/2020.

TransferMate (2020): Währungsrechner: Historische Wechselkurse. Available online at https://transfermate.io/de/whrungsrechner-historische-wechselkurse.asp, updated on 9/2/2020, checked on 9/2/2020.

University of Warwick (2020): Used Nissan LEAF batteries given “second life” thanks to WMG, University of Warwick. Available online at https://warwick.ac.uk/newsandevents/pressreleases/used_nissan_leaf/, updated on 8/6/2020, checked on 8/6/2020.

USABC (1996): Electric Vehicle Battery Test Procedures Manual. Revision 2. Edited by United States Advanced Battery Consortium (USABC). Available online at https://www.uscar.org/guest/publications.php, checked on 7/6/2020.

USGS (2020): Mineral Commodity Summaries 2020. With assistance of U.S. Department of the Interior, U.S. Geological Survey, checked on 5/24/2020.

Vaalma, Christoph; Buchholz, Daniel; Weil, Marcel; Passerini, Stefano (2018): A cost and resource analysis of sodium-ion batteries. In *Nat Rev Mater* 3 (4). DOI: 10.1038/natrevmats.2018.13.

van Notten, Philip (2005): Writing on the Wall. Scenario Development in Times of Discontinuity.

Vattenfall (2018): Second Life Batterien: Potential für Energiespeicher. Available online at https://group.vattenfall.com/de/newsroom/blog-news-presse/blog/2018/september/second-life-batterien-energiespeicher, updated on 8/5/2020, checked on 8/5/2020.

Volkswagen (2018): Volkswagen offers First Glimpse of Mobile Charging Station. Available online at https://www.volkswagenag.com/en/news/stories/2018/12/the-first-power-bank-for-the-e-car.html#, updated on 6/26/2020, checked on 8/4/2020.

Volkswagen (2019): Volkswagen und Northvolt schließen Joint Venture für Batterieproduktion. Available online at https://www.volkswagen-newsroom.com/de/pressemitteilungen/volkswagen-und-northvolt-schliessen-joint-venture-fuer-batterieproduktion-5316, updated on 6/3/2020.000Z, checked on 6/3/2020.

Wang, Michael (2019): The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET). Version GREET Excel October 2019: Argonne National Laboratory.

Wang, Xue; Gaustad, Gabrielle; Babbitt, Callie W. (2016): Targeting high value metals in lithium-ion battery recycling via shredding and size-based separation. In *Waste management (New York, N.Y.)* 51, pp. 204–213. DOI: 10.1016/j.wasman.2015.10.026.

Wegener, Kathrin; Chen, Wei Hua; Dietrich, Franz; Dröder, Klaus; Kara, Sami (2015): Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries. In *Procedia CIRP* 29, pp. 716–721. DOI: 10.1016/j.procir.2015.02.051.

Weicker, Phillip (2014): A systems approach to lithium-ion battery management. Boston: Artech House. Available online at http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&AN=1155207.

Xiao, Jiefeng; Li, Jia; Xu, Zhenming (2017): Novel Approach for in Situ Recovery of Lithium Carbonate from Spent Lithium Ion Batteries Using Vacuum Metallurgy. In *Environmental science & technology* 51 (20), pp. 11960–11966. DOI: 10.1021/acs.est.7b02561.

Xiaxiao, Zhang; Li, Li; Ersha, Fan; Yifan, Bian; Feng, Wu; Renjie, Chen (2018): Toward sustainable and systematic recycling of spent rechargeable batteries. In *Chemical Society reviews* (47), pp. 7239–7302. DOI: 10.1039/C8CS00297E.

Yuan, Chris; Deng, Yelin; Li, Tonghui; Yang, Fan (2017): Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Annals, 66(1), 53-56. In *CIRP Annals* 66 (1), pp. 53–56. DOI: 10.1016/J.CIRP.2017.04.109.

Zhu, Shu-guang; HE, Wen-zhi; LI, Guang-ming; ZHOU, Xu; ZHANG, Xiao-jun; HUANG, Ju-wen (2012): Recovery of Co and Li from spent lithium-ion batteries by combination method of acid leaching and chemical precipitation. In *Transactions of Nonferrous Metals Society of China* 22 (9), pp. 2274–2281. DOI: 10.1016/S1003-6326(11)61460-X.

Ziemann, Saskia; Müller, Daniel B.; Schebek, Liselotte; Weil, Marcel (2018): Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. In *Resources, Conservation and Recycling* 133, pp. 76–85. DOI: 10.1016/j.resconrec.2018.01.031.

Zubi, Ghassan; Dufo-López, Rodolfo; Carvalho, Monica; Pasaoglu, Guzay (2018): The lithium-ion battery: State of the art and future perspectives. In *Renewable and Sustainable Energy Reviews* 89, pp. 292–308. DOI: 10.1016/j.rser.2018.03.002.

Annex

A. Additional tables

Table A.1 Average battery size (rounded, in kWh) of newly registered BEV and PHEV passenger car electric vehicles in Europe from 2011 to 2030. The numbers for 2011 to 2023 are based on worldwide EV sales from 2011 to 2019 and projections from 2020 to 2023 (Takeshita et al. 2019). The values were linearly approximated to calculate values until the year 2030.

kWh	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
BEV	22	22	35	35	40	50	54	58	65	61	61	65	66	68	70	72	73	75	77	79
PHEV	-	11	12	11	12	12	12	13	13	16	17	19	20	21	23	24	25	27	28	30

Table A.2 Historic data of market share of newly registered passenger car BEV and PHEV vehicles in the EU from 2011 to 2019 (EAFO 2020a), and projections from 2020 to 2030 for the sensitivity analysis (rounded, in %).

%	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
BEV	0	0	0	0	0	0	1	1	2	2	2	3	4	6	8	10	12	14	16	19
PHEV	0	0	0	0	1	1	1	1	1	1	1	2	2	2	3	4	4	5	6	8
BEV	0	0	0	0	0	0	1	1	2	2	3	4	5	8	11	13	16	18	21	25
PHEV	0	0	0	0	1	1	1	1	1	1	2	2	2	3	4	5	6	7	8	10
BEV	0	0	0	0	0	0	1	1	2	3	3	5	7	9	13	17	20	23	27	31
PHEV	0	0	0	0	1	1	1	1	1	2	2	2	3	4	5	6	7	9	10	13

Table A.3 Historic data on BEV and PHEV sales in the EU from 2011 to 2019 (EAFO 2020a) and projections from 2020 to 2030 for the sensitivity analysis (rounded, in thousand sales) .

10^3	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
BEV	8	13	21	31	48	53	83	132	246	324	353	465	610	854	1.197	1.511	1.765	2.062	2.408	2.813
PHEV	-	8	25	25	71	65	86	108	140	189	200	237	280	353	444	535	644	776	934	1.125
BEV	8	13	21	31	48	53	83	132	246	360	415	581	814	1.140	1.596	2.015	2.353	2.749	3.211	3.750
PHEV	-	8	25	25	71	65	86	108	140	210	235	296	373	470	593	714	859	1.035	1.246	1.500
BEV	8	13	21	31	48	53	83	132	246	396	477	697	1.017	1.424	1.994	2.519	2.942	3.436	4.013	4.688
PHEV	-	8	25	25	71	65	86	108	140	231	270	355	466	588	741	892	1.074	1.293	1.557	1.875

Table A.4 Market share of cathode chemistries for BEV passenger car sales from 2011 to 2019 (calculations based on (Takeshita et al. 2019)) and projections from 2020 to 2030 (in % of total kWh passenger car sales).

%	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
NMC111	100	84	49	51	42	20	5	2	1	2	1	1	1	0	0	0	0	0	0	0

NMC532	0	0	0	0	0	14	20	16	8	11	6	3	3	2	0	0	0	0	0	0
NMC622	0	0	0	0	0	2	23	29	36	38	29	28	27	24	20	18	16	14	12	10
NMC811	0	0	0	0	0	0	0	1	3	10	30	41	45	52	60	64	68	72	76	80
NCA	0	16	51	49	58	65	53	52	53	39	34	27	24	22	20	18	16	14	12	10

Table A.5 Market share of cathode chemistries for PHEV passenger car sales from 2011 to 2019 (calculations based on (Takeshita et al. 2019)) and projections from 2020 to 2030 (in % of total kWh passenger car sales).

%	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
NMC111	100	95	90	89	83	63	68	54	46	16	6	3	2	1	0	0	0	0	0	0
NMC532	0	5	11	11	8	7	8	11	22	19	14	8	3	2	1	0	0	0	0	0
NMC622	0	0	0	0	9	30	24	35	30	36	50	56	57	58	58	54	50	45	35	25
NMC811	0	0	0	0	0	0	0	0	2	29	30	34	38	39	41	46	50	55	65	75

Table A.6 Weight shares of materials inside the different LIB types of the scenario analysis (in kg/kWh). The NMC variations are in a pouch cell format, the NCA cell is cylindrical. For lithium, both the required quantity of the market commodity "lithium carbonate", as well as the amount of pure lithium inside the lithium carbonate is given. Own calculations based on (Takeshita et al. 2018, 2019).

kg/kWh	**Function**	**Material**	**NMC111**	**NMC532**	**NMC622**	**NMC811**	**NCA**
Cathode	Active Material	(Lithium carbonate)	(0,589)	(0,588)	(0,586)	(0,583)	(0,520)
		Lithium	0,111	0,110	0,110	0,110	0,098
		Nickel	0,311	0,467	0,558	0,741	0,760
		Manganese	0,292	0,262	0,174	0,087	-
		Cobalt	0,313	0,188	0,187	0,093	0,041
		Aluminium	-	-	-	-	0,011
	Conductor	AB	0,069	0,069	0,069	0,069	0,018
	Binder	PVDF	0,045	0,045	0,045	0,045	0,012
	Current collector	Aluminium foil	0,126	0,126	0,126	0,126	0,104
Anode	Active Material	Natural graphite	0,908	0,908	0,908	0,908	0,926
	Binder	SBR	0,015	0,015	0,015	0,015	0,014
	Binder	CMC	0,015	0,015	0,015	0,015	0,014
	Current collector	Copper foil	0,417	0,417	0,417	0,417	0,260
Electro-lyte	Solvent	EC	0,238	0,238	0,238	0,238	0,174
	Solvent	DMC	0,238	0,238	0,238	0,238	0,174
	Lithium salt	LiPF6	0,077	0,077	0,077	0,077	0,057
Se per ator		PE	0,139	0,139	0,139	0,139	0,093
Case (pouch)		Aluminium tab	0,017	0,017	0,017	0,017	-
		Nickel tab	0,058	0,058	0,058	0,058	-
		PET/Al laminate	0,078	0,078	0,078	0,078	-
Case (cyl.)		Nickel plated iron	-	-	-	-	0,439
		Insulator, tape	-	-	-	-	0,126
		Top cover	-	-	-	-	0,117
Module		Aluminium	0,155	0,155	0,155	0,155	0,151
		PP/PE	0,065	0,065	0,065	0,065	0,063
		Steel	0,053	0,053	0,053	0,053	0,052
		Electronics	0,003	0,003	0,003	0,003	0,003
Pack	BMS	Steel	0,081	0,081	0,081	0,081	0,080
	BMS	Copper	0,102	0,102	0,102	0,102	0,100
	BMS	Printed curcuit board	0,020	0,020	0,020	0,020	0,020
	Thermal management	Aluminium	0,183	0,183	0,183	0,183	0,179
	Thermal management	Steel	0,020	0,020	0,020	0,020	0,020
	Packaging	Aluminium	0,428	0,428	0,428	0,428	0,418
	Packaging	PP/PE	0,031	0,031	0,031	0,031	0,030
	Packaging	Steel	0,122	0,122	0,122	0,122	0,120
	Packaging	WEEE	0,031	0,031	0,031	0,031	0,030

Table A.7 Emissions of raw material production in kg $CO2_e$/kg of raw material. The values originate from the EU PEF database (GreenDelta GmbH 2020). For the boxplot diagrams in subchapter 2.2.10, the values in this table were supplemented by values found in the Argonne GREET Excel software (Wang 2019).

	Function	**Material**	**Process name**	*kg $CO2_e$/ kg of material*
Cathode	Active Material	Lithium	Lithium carbonate production	2,070
		Nickel	Nickel production	10,707
		Manganese	Manganese production	12,456
		Cobalt	Cobalt production	36,053
		Aluminium	Aluminium sheet rolling, single route	11,827
	Conductor	AB	Carbon black	2,654
	Binder	PVDF	Polyvinylidene fluoride (PVDF), production	8,545
	Current collector	Aluminium foil	Aluminium foil	13,585
Anode	Active Material	Natural graphite	Carbon black	2,654
	Binder	SBR	Styrene-butadiene rubber (SBR) fiber, production	3,593
	Binder	CMC	Carboxymethyl cellulose production, production	4,388
	Current collector	Copper foil	Copper oxide	3,474
Electro-lyte	Solvent	EC	Ethylene carbonate production, production	1,631
	Solvent	DMC	Dimethyl carbonate production, production	2,316
	Lithium salt	LiPF6	Lithium hydroxide production	5,740
Seperator		PE	Plastic film, PP, production mix (GHG per m^2)	0,139
Case (pouch)		Aluminium tab	Aluminium sheet rolling	11,827
		Nickel tab	Nickel production	10,707
		PET/Al laminate	Aluminium sheet rolling	11,827
Case (cyl.)		Nickel plated iron	Steel cold rolled coil	2,747
		Insulator, tape	Plastic film, PP, production mix (GHG per m^2)	0,096
		Top cover	Aluminium sheet rolling	11,827
Module		Aluminium	Aluminium sheet rolling	11,827
		PP/PE	Plastic film, PP, production mix (GHG per m^2)	0,096
		Steel	Steel cold rolled coil	2,747
		Electronics	Copper oxide	3,474
Pack	BMS	Steel	Steel cold rolled coil	2,747
	BMS	Copper	Copper oxide	3,474
	BMS	Printed curcuit board	Populated Printed wiring board (PWB) (2-layer)	153,704
	Thermal management	Aluminium	Aluminium sheet rolling	11,827
	Thermal management	Steel	Steel cold rolled coil	2,747
	Packaging	Aluminium	Aluminium sheet rolling	11,827
	Packaging	PP/PE	Plastic film, PP, production mix (GHG per m^2)	0,096
	Packaging	Steel	Steel cold rolled coil	2,747
	Packaging	WEEE	Populated Printed wiring board (PWB) (2-layer)	153,704

Table A.8 Average market prices in 2019 of raw materials. Derived from DERA (DERA 2020).

Material	**Market commodity**	*€/ kg of material*
Lithium	Lithium-carbonate, min. 99.5% Li2Co3, battery grade, sport price, ex works, domestic China	9,286
Nickel	LME, primary nickel, min. 99.8%, cash, in LME warehouse	11,700
Manganese	Electrolytic manganese (EMM), >= 99,7%, export (fob), domestic	1,704
Cobalt	LME cobalt, min. 99.8 % cash, in LME warehouse	30,218
Aluminium	LME, high grade primary aluminium, cash, in LME warehouse	1,597
Graphite	Crystalline large flake Graphite, 94-97% C, +80 mesh, cif main European port	0,739
Copper	LME, grade A copper, cash, in LME warehouse	5,257
Steel	LME Steel HRC N. America (Platts)	0,497

Table A.9 Political relevance of LIB metals and graphite. Values derived from the 2017 and 2020 EU list of critical raw materials (European Commission 2017a; Eynard et al. 2020a).

Material	**Economic importance (2020)**	**Supply Risk (2020)**	**EU import reliance (2017)**
Lithium	3,1	1,6	86%
Nickel	4,9	0,5	59%
Manganese	6,7	0,9	89%
Cobalt	5,9	2,5	32%
Aluminium	5,4	0,6	65%
(Natural) Graphite	3,2	2,3	99%
Copper	5,3	0,3	82%
Steel	6,8	0,5	74%

Table A.10 LIB demand in the EU 2020, 2025 and 2030 for three market share scenarios (in kWh, rounded).

	2020		**2025**		**2030**
Low scenario	22.561.241	→	93.793.008	→	254.241.111
Base case	25.068.045	→	125.057.344	→	338.988.147
High scenario	27.574.850	→	156.321.680	→	423.735.184

B. Additional graphs

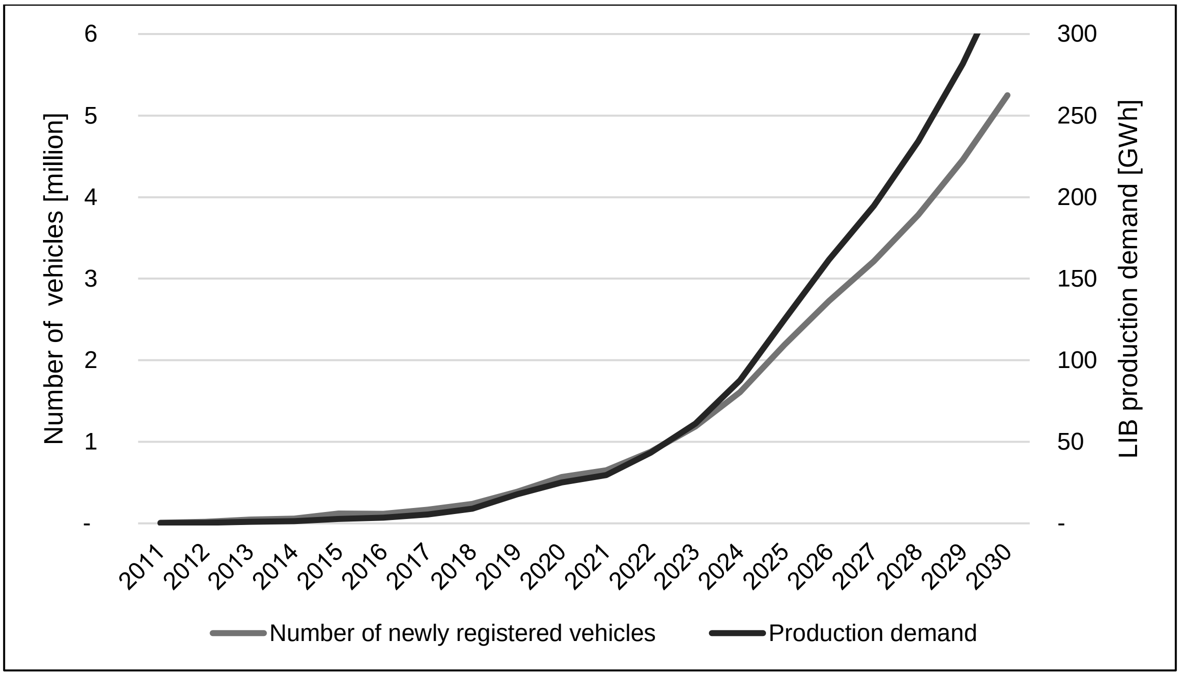


Figure B.1 Number of newly registered vehicles and battery production demand (in GWh) from 2011 to 2030.

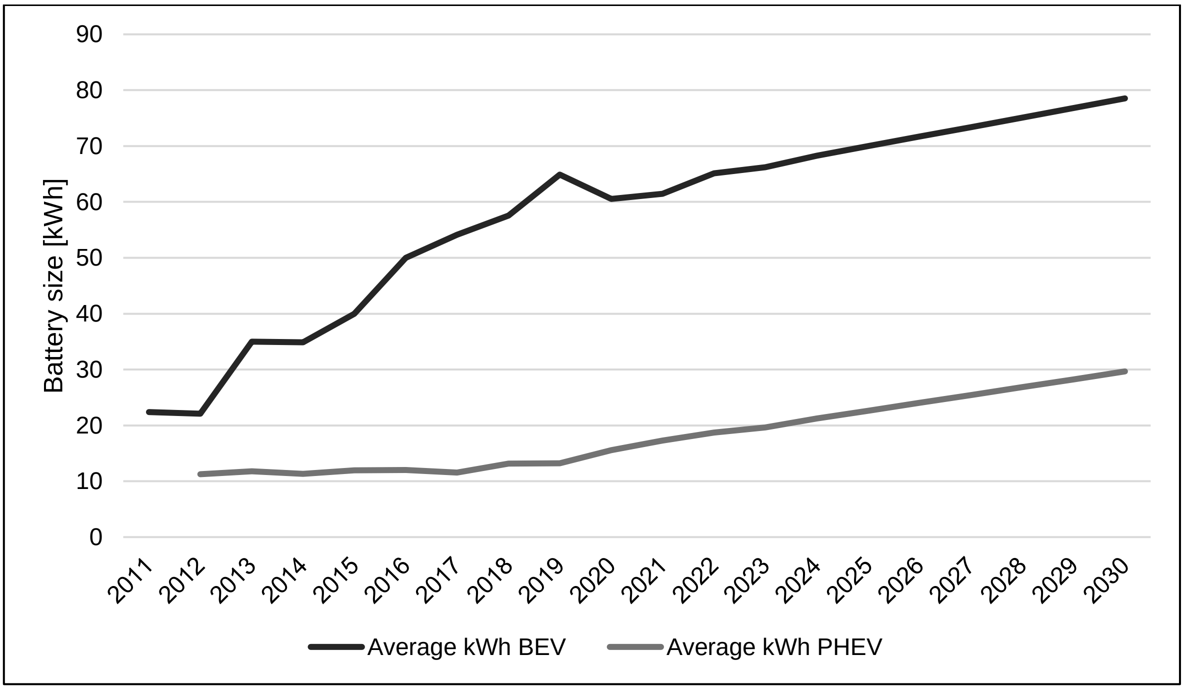


Figure B.2 Development of average battery sizes from BEV and PHEV vehicles from 2011 to 2030.

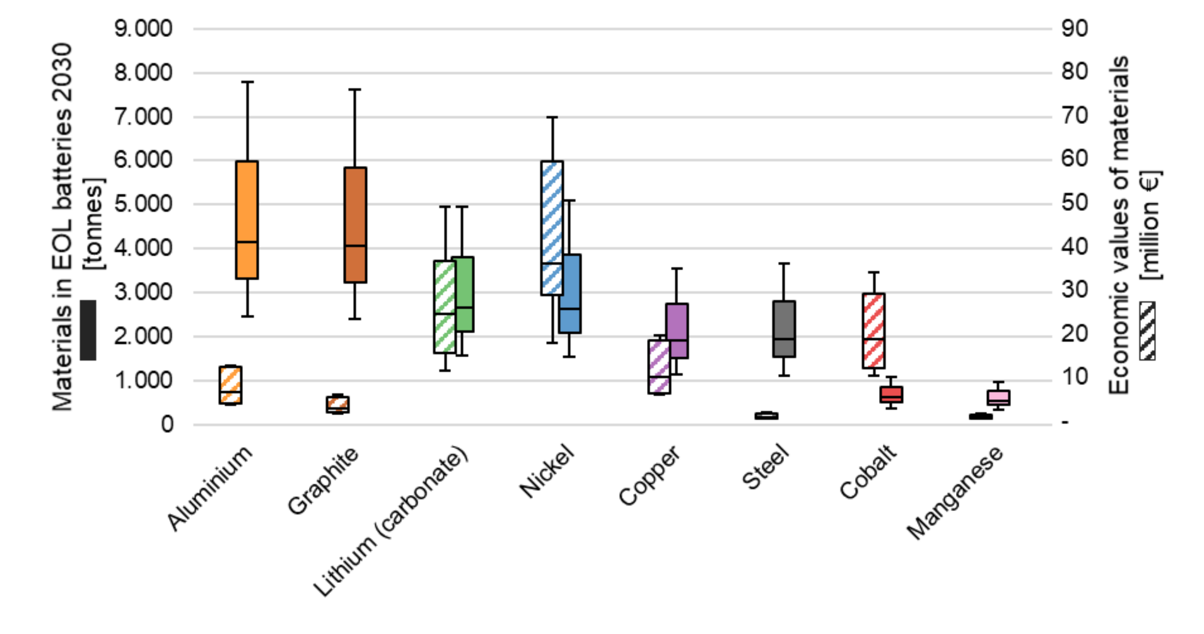


Figure B.3 Materials inside LIBs that reach their EOL in 2025, and the corresponding economic value. Results for 3 lifetime and 3 raw material price scenarios.

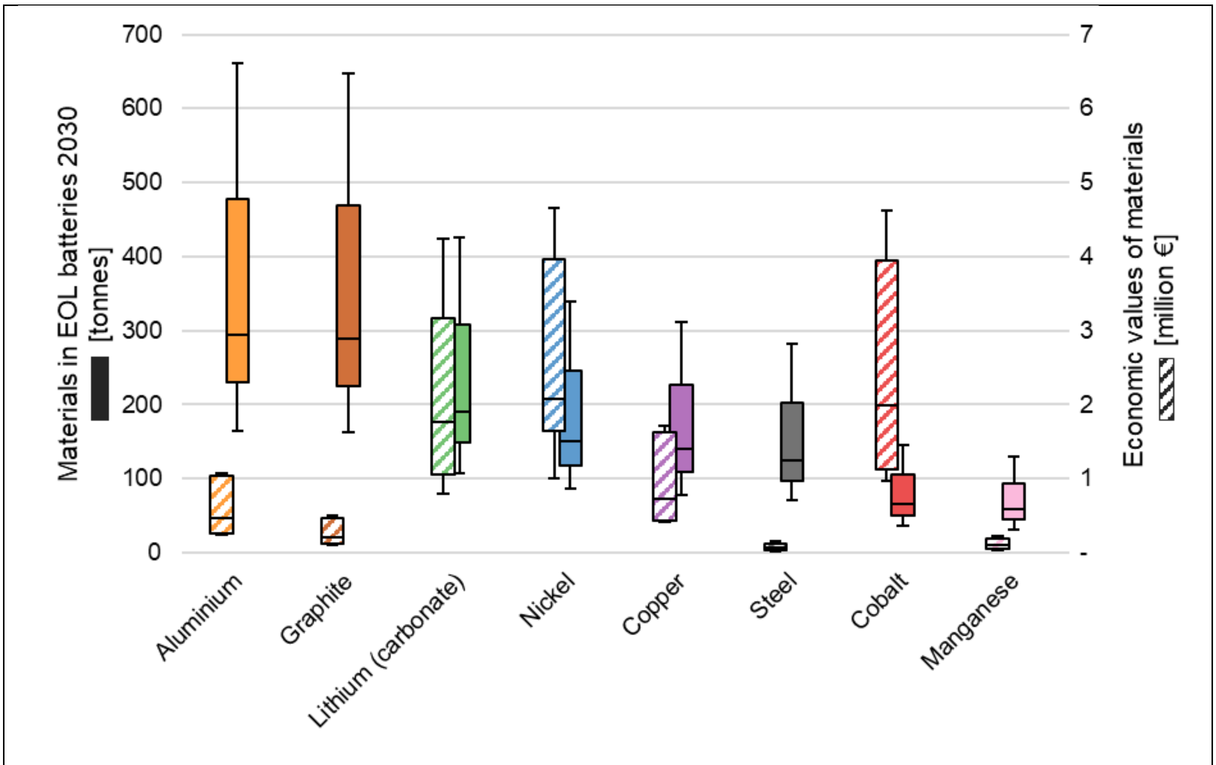


Figure B.4 Materials inside LIBs that reach their EOL in 2020, and the corresponding economic value. Results for 3 lifetime and 3 raw material price scenarios.

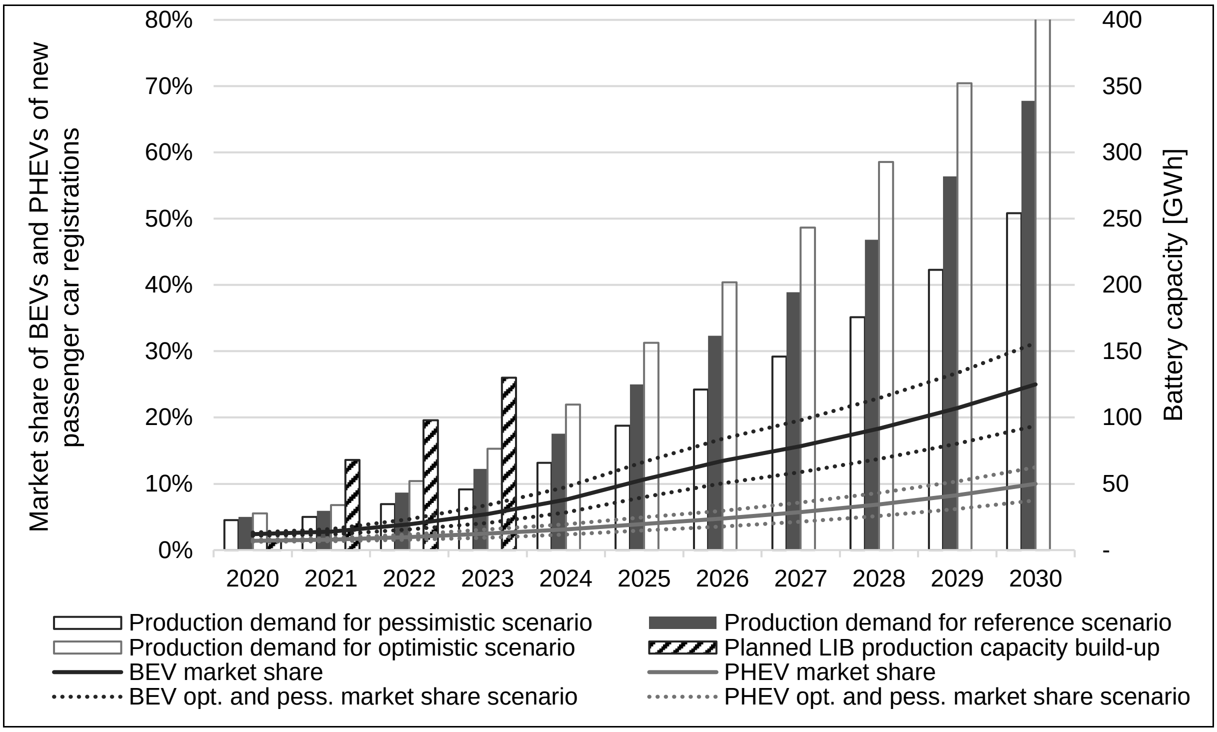


Figure B.5 Sensitivity of the LIB market scenarios for BEVs and PHEVs in EU (low, reference, and high market share scenario). Left axis: Scenarios for market shares of BEVs and PHEVs of newly registered passenger cars in the EU; Right axis: LIB production capacity necessary to meet BEV and PHEV passenger car demand (in GWh) and announced production build-up (non-exhaustive). Own calculation based on (EAFO 2020a), (ACEA 2020), (ICCT 2019), and press releases.

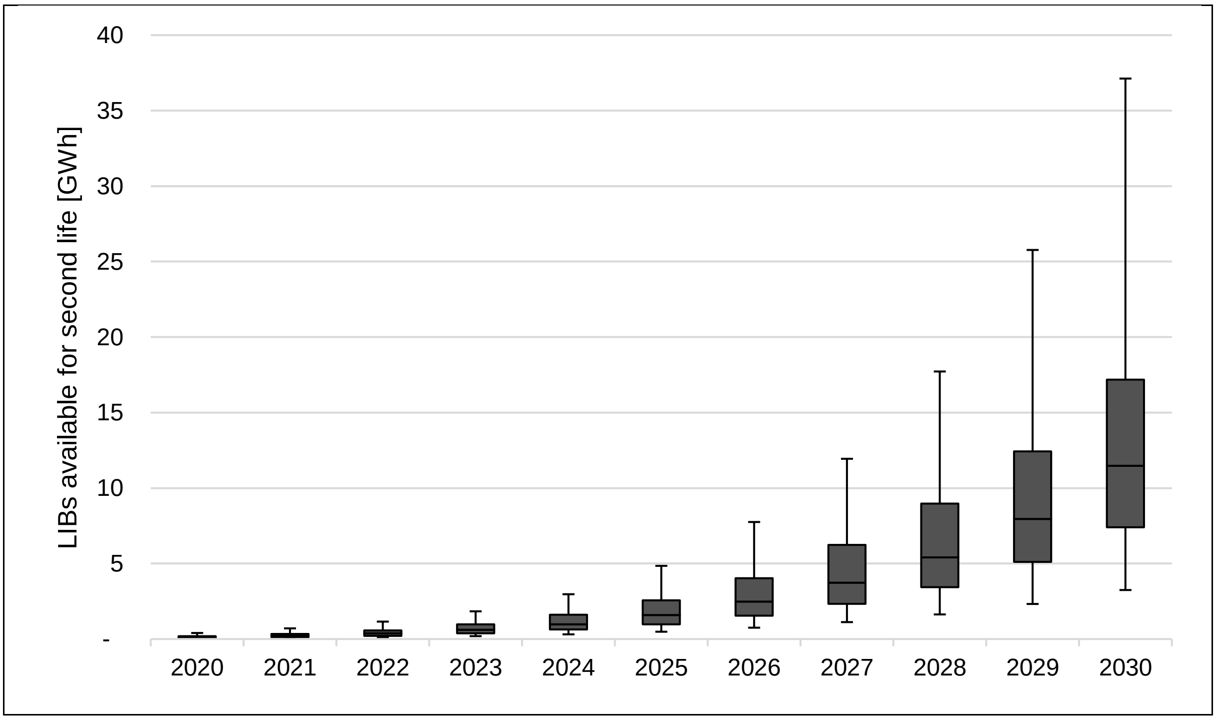


Figure B.6 GWh of LIBs eligible for second life. Results for the sensitivity analysis (3 market share, 3 lifetime and 3 reuse scenarios).

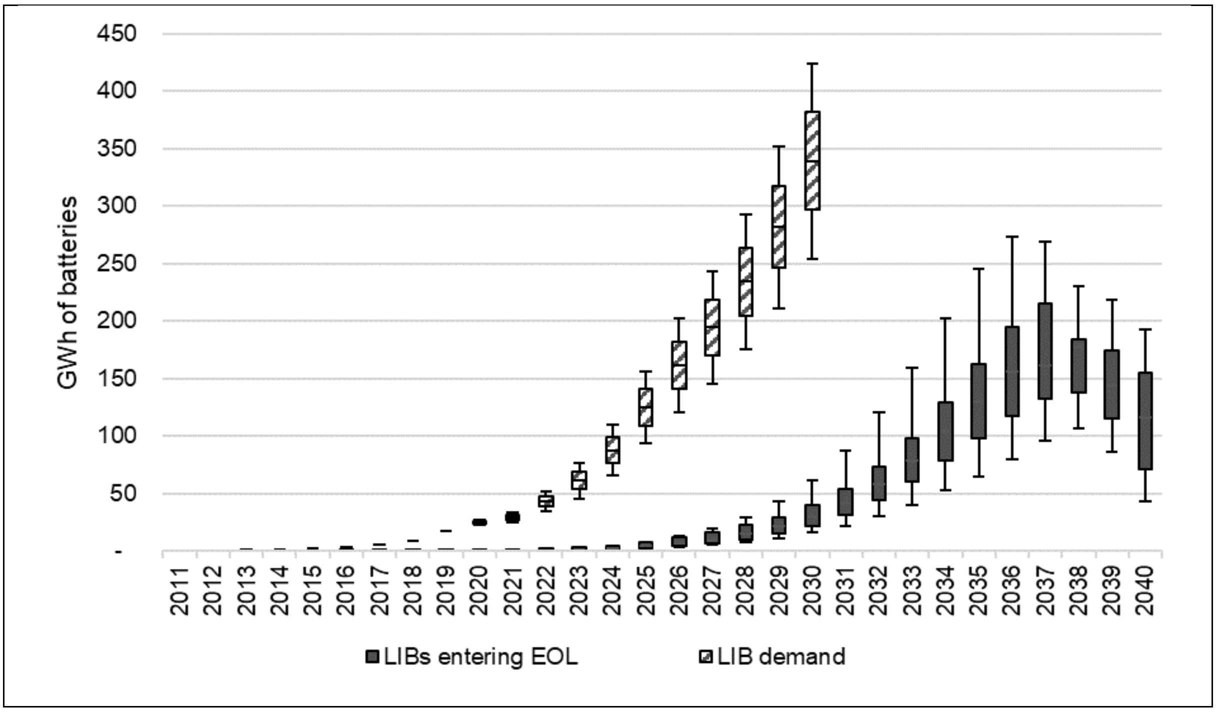


Figure B.7 Batteries entering EOL (9 scenarios) and battery demand (3 scenarios). Under the assumption that there are no more EV sales after 2030.

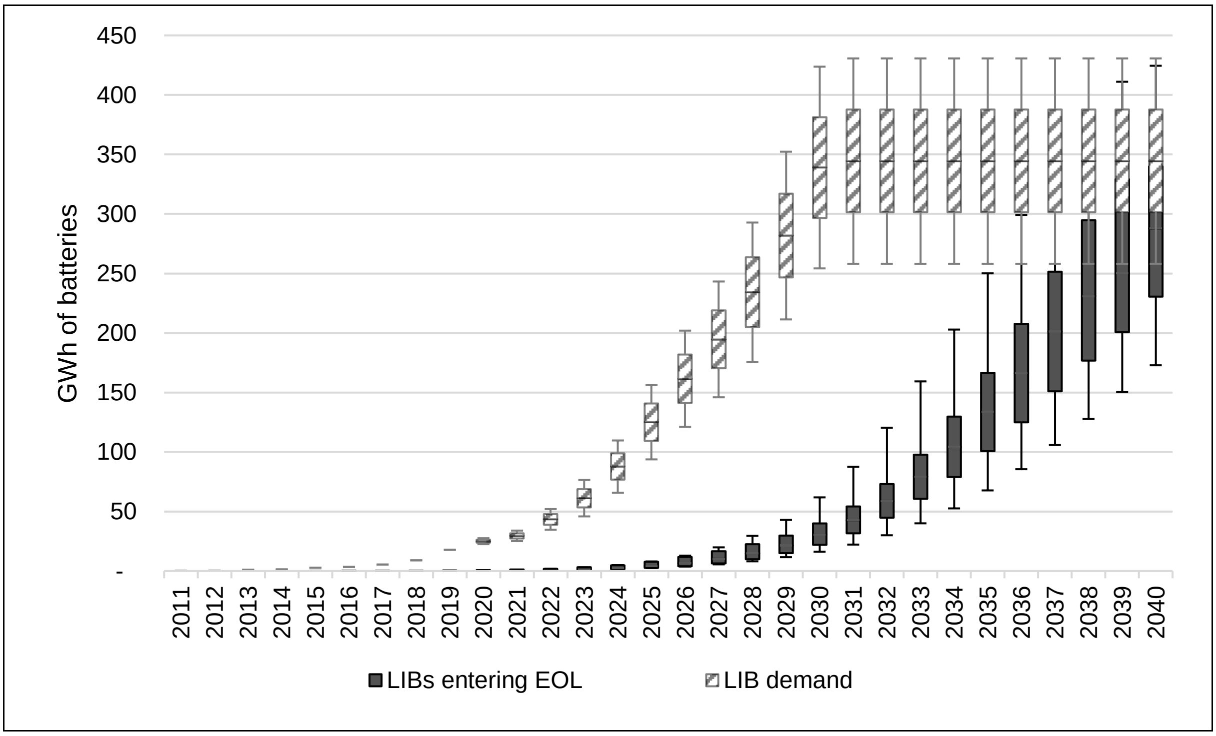


Figure B.8 Batteries entering EOL (9 scenarios) and battery demand (3 scenarios). Under the assumption that EV sales are constant after 2030.

C. Pseudo code to calculate material flows

The following pseudo code presents the logic to calculate the material amounts in the Excel spreadsheet with VBA. The shown calculation only covers BEV vehicles and only 1 lifetime scenario.

```
A = Row in Worksheet1 that contains yearly new registered kWh of BEVs
B = Row number in Worksheet1 after which material amount results are listed
For a = 1 To 8 'counter for the 8 different materials
For b = 21 To 40 'columns of the year 2011 to 2030
Material sum = 0
For c = 1 To 20 'counter to go back in time
      For d = 1 To 5 'counter for different LIB types
            Share of LIB type in BEVs = Worksheet1.Cells(d, b - c)      [1]
            Newly registered kWh BEVs = Worksheet1.Cells(A, b - c)      [2]
            kWh per LIB type = [1] * [2]                                [3]
            Material shares = Worksheet2.Cells(a, d)                    [4]
            Battery lifetime share = Worksheet3.Cells(1, c)             [5]
            Material amount = [3] * [4] * [5]                           [6]
            Material sum = Material sum + [6]                           [7]
      Next d
Next c
Worksheet1.Cells(B + a, b).Value = [7]
Next b
Next a
```