Master Thesis

EU Transition to Electric Mobility in Private Passenger Transport: Effects on Cobalt and Lithium Demand

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Abstract

Efforts to mitigate climate change have led to a rise in demand for decarbonised transport. The electrification of passenger cars is imminent, with battery powered propulsion being the most promising path of technology. Cobalt and Lithium play important roles in current state-of-the-art Lithium-ion batteries, which makes their supply crucial for the European Union to achieve its self-set goal of becoming a world leader in battery technology and its aim for an Electric Vehicle (EV) market share of 30% in 2030. Thus, in this thesis, the future Cobalt and Lithium demand is modelled by means of three scenarios enabling the assessment of the supply side. The passenger car demand, which represents the basis for all scenarios is built using a stock-driven Material Flow Analysis (MFA) model to estimate the market up to 2050. It turns out, that the technology development has a sizeable effect on demand in the long term. The near future demand is dominated by the utilised battery capacities and minor energy density improvements.

Content

Abbreviations

(k)Wh	(kilo-)watt-hour
BEV	Battery Electric Vehicle
BMS	Battery Management System
CRM	Critical Raw Material
EoL	End of Life
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse gas emissions
HE-NMC	High Energy – Nickel Manganese Cobalt
HEV	Hybrid Electric Vehicle
HVS	High Voltage Spinel
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
LMO	Lithium Manganese Oxide
MFA	Material Flow Analysis
NCA	Nickel Cobalt Aluminium Oxide
NMC	Nickel Manganese Cobalt
PHEV	Plug-In Hybrid Electric Vehicle
RMSE	Root Mean Square Error
SSE	Solid State Electrolyte

1. Introduction

Climate change is an ever more apparent concern and the need to act is recognized in the Paris agreement which entered force in November 2016. Its goal of keeping global temperature rise to below two degrees of pre-industrial levels includes the application of a low-carbon technology framework. The transport sector is accountable for 20% of the EU's emissions of carbon dioxide (CO2), thus, decarbonising road transport as its biggest contributor is of considerable importance. The EU and its member states agreed on an emission reduction of 37,5% for new cars in 2030 compared to numbers of 2020. (European Environment Agency 2018)

Electric Vehicles (EVs) are currently dealt as the most promising technology path to reach those emission limits. Battery Electric Vehicles (BEVs) powered by Lithium-ion Batteries (LIBs) demonstrated their feasibility with the market entry of *Tesla*. Since then, more adopters entered the market and the price per kilowatt-hour (kWh) decreased and EVs became recognized as possible alternatives to conventional fossil fuel powered vehicles. The major concerns about this technology are the considerably higher purchase price and the limited range on one charge. Governments in the EU are granting monetary incentives upon the customer's investment in a new EV but even then, prices are usually higher than the comparable Internal Combustion Engine (ICE) car. Thus, the EV's purchase price decrease is of uttermost importance to make this technology an attractive alternative for the consumer.

As much of new eco-technology depends on a greater variety of minerals, LIBs are no exemption. The major share of an EV's price is down to the battery module which consists of battery packs which contain the cells with the defining and name-giving battery chemistry. The cell's cathode contains Cobalt, which is accountable for most of the performance increases that lead to the state-of-the-art LIB we have today. The price for raw materials make up for 70% - 80% of the cells costs (Olivetti et al. 2017), which is why a reduction of those materials – especially Cobalt – is crucial to reduce the battery's overall costs. The development efforts towards Cobalt reduction are further highlighted in section 2.3.

Cobalt is recognized as a Critical Raw Material (CRM) by the European Commission in the "communication on the list of critical raw materials 2014" due to its impact on the economy in case of a supply shortage. The supply risk comes from the low number of producing countries; 72% of Cobalt in 2018 originated from The Democratic Republic of Congo (Darton Commodities Limited 2019). Most of the Cobalt supply is mined as a co- or by-product (primarily with Nickel and Copper) which increases its dependence. The price volatility of Cobalt arises from supply uncertainties and a lack of transparency (Azevedo et al. 2018).

Lithium is the name-giving material because of the metal's special properties: It is the lightest of all metals and provides the largest energy density. Lithium is currently either used in the form of Lithium Carbonate (Li_2CO_3) with 19% Lithium or Lithium Hydroxide (LiOH) with 29% Lithium. The latter has a higher grade and is used in today's cells with the highest energy densities. The production requires further processing steps or more energy intensive sourcing from rock. Pure Lithium metal has a potential market for future battery systems but is currently not applied on a big scale. The supply of this material has a more oligopolistic structure with eight producing countries. Although Lithium is an abundant mineral, its price is currently volatile as most of its production is concentrated in China (Sanderson 2019). Lithium (and Cobalt) were considered as "minor metals" so far, which reasons the low transparency and liquidity around pricing. This issue could disappear with a matured and increased market. (Azevedo et al. 2018)

Cobalt and Lithium represent bottleneck materials for the unobstructed introduction of EVs. This study aims to gain insight in the future material flows of Cobalt and Lithium in the EU, coming from the increased battery demand, accelerated by stricter emission goals and boosted EV market shares. Three scenarios – mainly differing in projected EV-demand and battery technology – show up the technology differences and the related projection in demand for Cobalt and Lithium. Future vehicle demand is modelled with the help of dynamic MFA and a temporal scope of the projections up to 2050.

2. Methodology

2.1. System Definition

The considered system covers the Cobalt and Lithium flows induced by battery demand for passenger-EVs in the EU. The same definition applies for the top five EU countries in terms of passenger vehicle market share (Germany, United Kingdom, France, Italy and Spain), where the individual development is examined. The system does not include batteries for HEVs nor conventional car batteries due to a difference in technical requirements and thus different technology and/or size of the battery. The system and its main drivers are highlighted in figure 1. The EU is chosen as the regional boundary due to its common set of legislation and compulsory regulations for the member states. All stocks (boxes) can be derived from the total vehicle fleet, which is subdivided into the share of EVs and the installed battery packs, which in turn inhere the Cobalt and Lithium. The hexagons represent the key influencing parameters for the system.

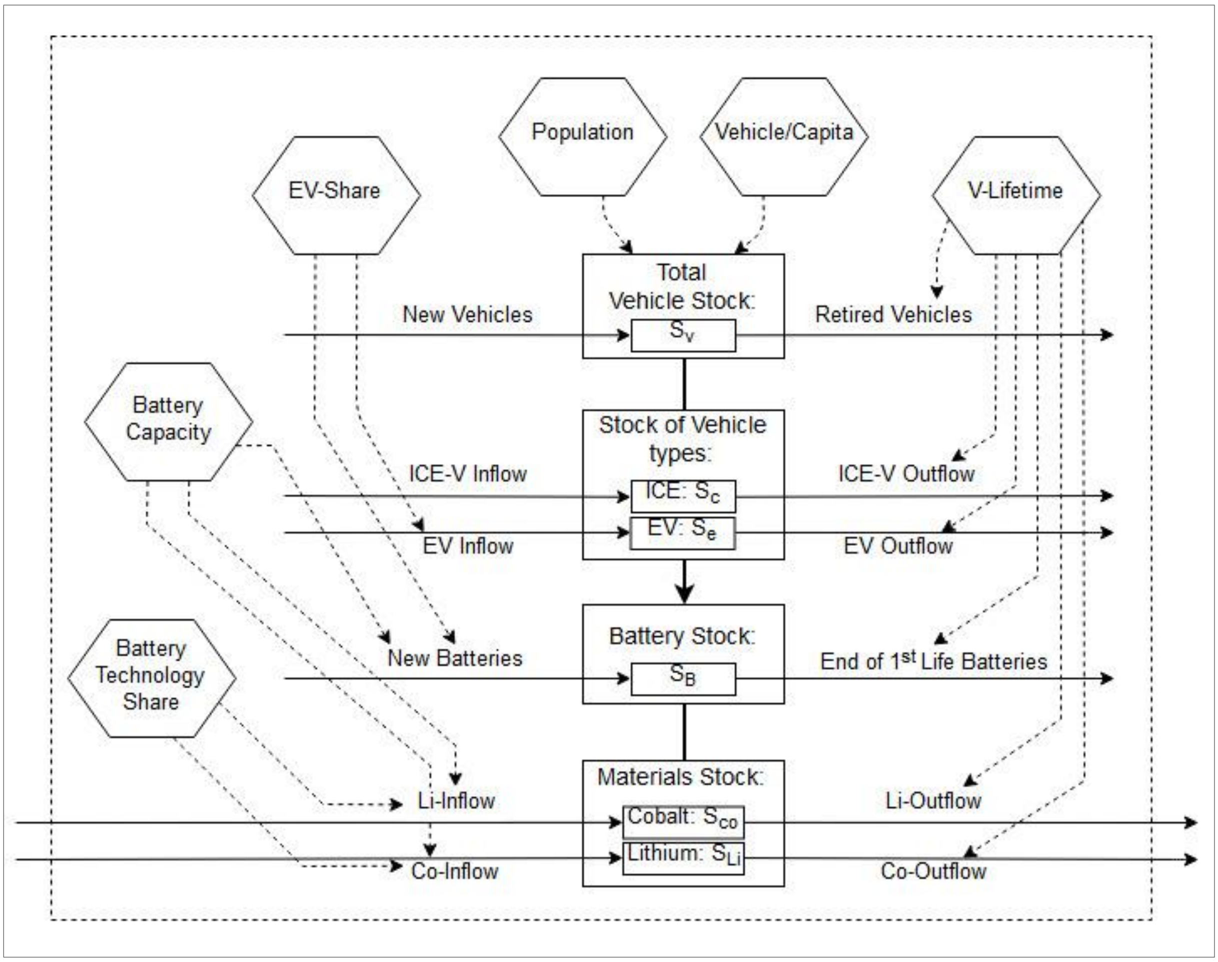


figure 1: dynamic model with cobalt and lithium flows

2.2. Model and Data

The key parameters and drivers (figure 1) for the calculations and projections (from 2018/19 on) of future flows include the total passenger car market to keep and built up the vehicle stock S_V and its share of EVs, which drives the battery demand. A Material Flow Analysis (MFA) model is built for the EU, Germany, the United Kingdom, France, Italy and Spain. The five countries (top 5) represent the main market drivers with 72% market-share in 2017 (The International Council of Clean Transportation 2018). The modelled demand is visualized in figure 2. and is mainly influenced by the vehicle lifetime, which is an adjustable but constant parameter for each model. The lifetime for the EU and each individual country is configured by comparing the modelled demand with actual sales data from the International Council of Clean Transportation (ICCT). The demand graphs with the overlaying sales curves can be found in the Appendix. Data from literature was taken as a reference to ensure realistic vehicle lifetimes. (Fridstrøm et al. 2016; Kolli et al. 2010). The consequences of this approach are dealt with in the sensitivity analysis (section 4). The resulting average lifetimes are as follows:

- EU: 17 years
- Germany: 13 years
- United Kingdom: 15 years
- France: 15 years
- Italy: 17 years
- Spain: 17 years

The high volatility - spikes in figure 2 - partly coincide with actual sales data, which is why original data wasn't modified apart from stock data for Germany; the country was separated until 1990 which lead to a big increase in stock after the reunification, plus the German council of transportation changed the approach of counting registered vehicles in 2008. Thus, the vehicle stock curve needed manual smoothing to compensate for the data gaps. This resulted in a noticeable different demand-curve shape compared to the EU and the other countries.

The underlying data for the stock driven modelling is based on historic vehicle stock (Mitchell 1998) and population (Eurostat 2018), from which the per capita vehicle ownership is derived. The data covers the years from 1960 to 2015. The calculated ownership data is then compared to another data set from *Eurostat* to verify the plausibility of the data. The per capita ownership data is then fitted with an S-curve (Pearl-Reed logistic) to find a saturation level to estimate future stock with the help of a population projection of the European Commission. On the country level, the population data and their projections were extracted from the national statistics offices *(Statistisches Bundesamt*, Germany; *Office for National Statistics*, UK; Institute National de la *Statistique et des Études Économiques*, France*; Istituto Nationale di Statistica*, Italy *and Instituto Nacional de Estadística*, Spain). The per capita vehicle ownership was then calculated in the same manner as for the whole EU.

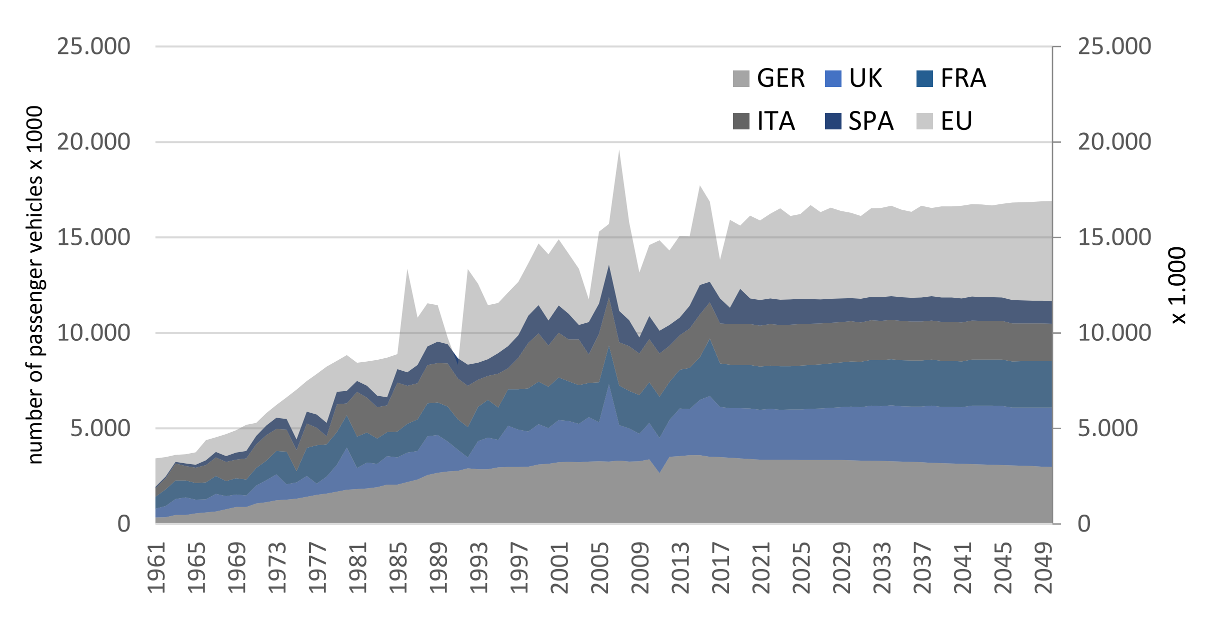


figure 2: passenger vehicle demand 1960-2050

The EV-share data for the EU and per individual country covers the years 2001 to 2017 but apart from some exceptions, a trend in EV-share is only recognizable from around 2010 onwards (The International Council of Clean Transportation 2018). Future trends are extrapolated by fitting a Gompertz curve on the data and including share-goals as future data points (dependant on the scenario). The Gompertz model is a frequently used sigmoid function to fit growth data. The curve and its parameters are explained below:

$$Gompertz\ function: f(t) = a * \exp(b * \exp(c * t))$$

a: Represents the upper asymptote and is manually restricted to "100" as the share is expressed in percent (scenario dependent variation)

b: Represents the displacement along the abscissa and allows for adjustment by software (*Matlab*)

c: Represents the negative growth rate. This parameter is adjusted according to the EV-share and/or the needed gradient to achieve envisaged goals

Norway has the highest percentual market share of EVs, reaching 58,4% in March 2019. (Karagiannopoulos, Solsvik 4/1/2019). The Gompertz curve was fitted to Norway's sales data to test the viability of the fitting with the help of a well-advanced country in terms of EV-development. (without the above-mentioned market share of 2019). The projected market share for 2019 is 1,5% below the reported share of March. The dark line represents the model, while the dark bars are actual sales data.

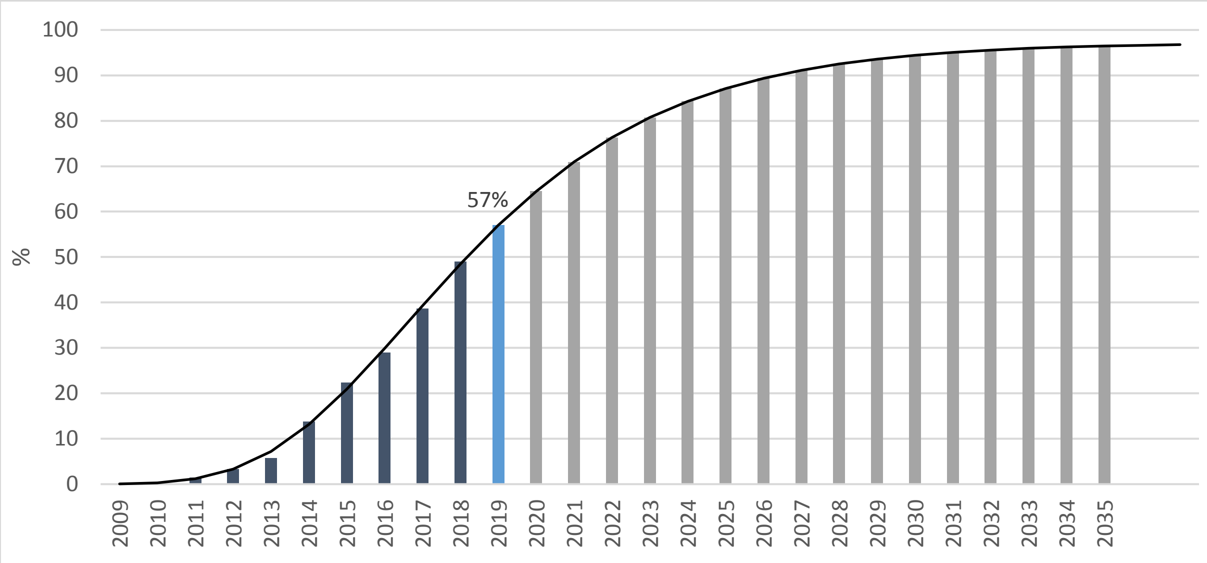


figure 3: EV-share of Norway, historic and projected

The battery capacity is a key influencing parameter as it is directly linked to the cars range which is a critical performance figure of today's EVs and the biggest customer concern (McKinsey&Company 2017). A higher capacity subsequently increases the volume and weight of a battery for the same battery technology. The Cobalt- and Lithium contents of a certain cell technology are defined by their mass content per energy (kg/kWh), meaning the content is linearly increased with the battery capacity.

The battery technology defines the Cobalt and Lithium content per kWh of state-of-the-art LIBs. The development step from NMC-622 to NMC-811 for instance would mean a 50% reduction in Cobalt content per kilowatt-hour while increasing the energy density (see section 2.3.1). This technology driver can balance the need for Cobalt and Lithium for the inevitable increase in battery capacity to make the EV competitive in terms of range.

2.3. Battery Technology Zoom-In

The different technology steps are broken down into generations which is common practise in the literature. The three sections represent the current development and possible technology break-throughs. Section 2.3.1 represents technologies up to the so-called generation 3a, which includes state-of-the-art technology and the introduction of nickel-rich chemistries (section 2.3.1). The evolutionary step within LIB technology is referred to as generation 3b, which implies drastic improvements of electrode components and the introduction of silicon shares in the anode (section 2.3.2). Section 2.3.3 informs about the potential of revolutionary technology beyond LIBs. Only researchable batteries suitable for application in EVs are considered.

2.3.1. State-of-the-Art

Today's state-of-the-art battery technology is based on the Transport of Lithium-Ions (Li^+) between a cathode and an anode via an electrolyte, hence the name Lithium-ion battery. The quality and the composition of these three components mainly determine the battery's performance. The batteries that are installed in electric devices and EVs are chosen and tailored to meet the individual needs for power density, energy density, cycle life, safety and price in the range of technical possibilities.

Battery technologies in use <u>today</u> are named after their cathode chemistry which determines the main performance differences. The letters represent the materials contained in the cathode chemistry (not the official abbreviation for the elements!).

- NMC – Nickel Manganese Cobalt (numbers behind represent the shares of the elements)
- NCA – Nickel Cobalt Aluminium Oxide (used by *Tesla*)
- LCO – Lithium Cobalt Oxide (very high Cobalt content, hence not suitable for EVs)
- LMO – Lithium Manganese Oxide (no Cobalt content, often used in EVs alongside NMC)
- LFP – Lithium Iron Phosphate (no Cobalt content, low energy density, more suitable for heavy duty applications due to cycle life)

Remark: The lack of the word "Lithium" doesn't mean that the cathode chemistry doesn't consists of Lithium. The LFP cathode can be coupled with a Lithium Titanite anode (see table 1*).*

A key parameter of interest is the energy density (Wh/kg), which is also linked to the usable Lithium share in the cathode, where it is intercalated. The anode is usually made from graphite and isn't altered in this stage of development. The following table lists some commercial battery types which are suitable for deployment in EVs:

table 1: Battery Technology, Generation 1 – 3a (Helbig et al. 2018; Olivetti et al. 2017)

Type	Cathode active material	Anode active material	Lithium content [kg/kWh]	Cobalt content [kg/kWh]
NMC-333 NMC-622 NMC-811	$Li(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$ $Li(Ni_{3/5}Mn_{1/5}Co_{1/5})O_2$ $Li(Ni_{4/5}Mn_{1/10}Co_{1/10})O_2$	graphite	0,139 0,126 0,111	0,394 0,19 0,094
NCA (Gen. II)	$Li(Ni_{1-x-y}Co_xAl_y)O_2$	graphite	0,112	0,143 (0,09)
LCO	$LiCoO_2$	graphite	0,113	1,04
LMO	$LiMn_2O_4$	graphite	0,12	-
LFP	$LiFePO_4$	graphite	n/s	-
LFP-LTO	$LiFePO_4$	$Li_4Ti_5O_{12}$	0,15	-

Remark: The different Lithium content for the NMC chemistries is down to their increase in energy density, not because the content has been actively reduced.

The Cobalt amount in the cathode has a strong influence on the performance as it improves the cathode's capability of intercalating Lithium. The market price of Cobalt was almost ten times that of Nickel in 2018. Mining is strongly concentrated in the politically unstable region of the Democratic Republic of Congo (DRC) – with 72% in 2018 (Darton Commodities Limited 2019). Most of the mineral is shipped to China which is the main producing country for battery grade Cobalt. These factors are strong incentives towards a reduction in Cobalt content. Engineering it out of the cell technologies is often connected with a decrease in thermal stability (NMC-622 towards NMC-811) and thus, increasing safety issues. Switching to Cobalt free battery chemistries currently implies lower energy density. Today's shares of batteries in EVs are shown in the following graph. (Azevedo et al. 2018):

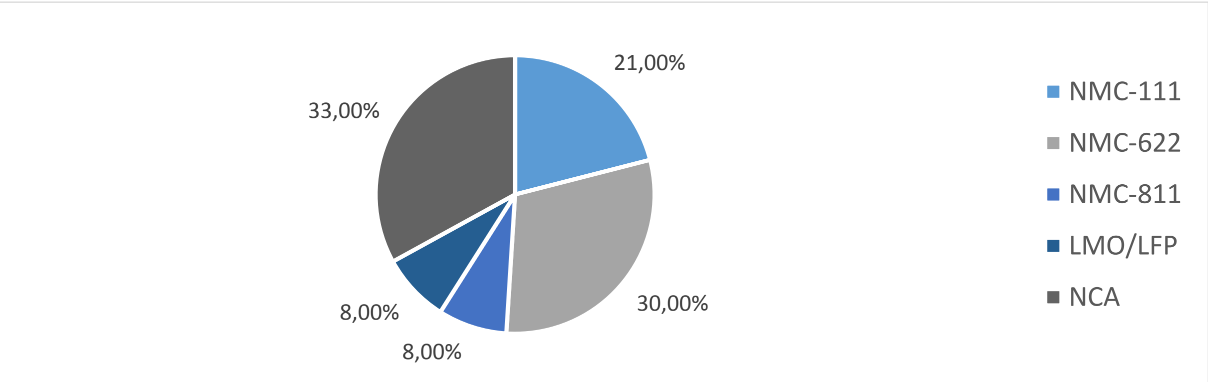


figure 4: Battery Chemistry share in EVs worldwide in 2018

Remark: So far, the utilised battery technology is strongly dependant on the manufacturer.

2.3.2. Advanced Li-ion technologies

The near future promises higher energy densities by modifying the cathode through coating and structure improvements. The anode material could be made from silicon. The cell chemistries of this generation 3b promise an increase in performance which leads to a higher energy density and therefore less Cobalt use per kilowatt-hour, resulting in higher overall capacity options to further increase range.

HE-NMC

High Energy Lithium rich NMC technology (HE-NMC) promises higher energies and thermal stability at lower costs. The basic principle behind the technology is a two-phase composite material for the anode, which is made from $x\ LiMO_2 * 1\text{-}x\ Li_2MnO_3$ (M stands for an NMC-chemistry, see section 2.3.1). This makes the technology "Lithium-rich", which is key to the performance increase. The downside of this technology is the low cycle life and a decaying voltage over the discharge. (Placke 2018)

HVS

Another cathode enhancement is the High Voltage Spinel (HVS) technology which promises high operating voltages and fast lithium diffusion (increasing responsiveness) at lower costs without the use of Cobalt. Furthermore, the over-lithiated spinal could be used as a pre-lithiation agent which would mean a higher practical energy density due to a decreased initial loss of Lithium – an issue in today's LIBSs. So far, the practical capacity of HVS in turn is low and fragile at elevated temperatures. (Placke 2018; Holtstiege et al. 2018)

Silicon Anode

The silicon anode is famous for bearing sizeable potentials. The high volumetric and gravimetric energy density make silicon the most promising anode material for the near future: it is very abundant in the earth's crust and has a tenfold higher gravimetric capacity than graphite. Unfortunately, the silicon anode leads to high volumetric changes of up to 400% which destroys the cell after a few cycles. The more practical approach is a gradual increase in silicon content. The composite anodes made from graphite and silicon have an increased performance thanks to the silicon while graphite stabilises the anode. (Placke 2018; Li et al. 2018)

2.3.3. Beyond Li-ion batteries

The technology steps listed below bear huge potential in terms of energy density and material savings but there are also many issues that need to be addressed before being fully deployable.

Solid State Electrolytes

Liquid Electrolytes are the technology of choice because of their excellent wetting of the anode, respectively the cathode and a good conductivity but they often suffer from electrochemical and thermal instability which decreases the safety of the system. The overall promises of solid-state batteries are higher energy densities and improved safety. The Solid-State-Electrolyte (SSE) also acts as the separator in the cell. The cathode materials are like those traditionally used LIBs (lithium transition metal oxides and sulphides). For the anode material, Lithium metal, lithium alloys and graphite can be considered. The all-solid-state batteries are classified after their SSEs into inorganic solid-electrolyte batteries or polymer batteries. Challenges to overcome are: volume change in the electrode material (see Silicon Anode), high resistance at the interface between electrode and electrolyte (bad wetting properties) and poor cycling stability. A break through in for this technology opens the possibilities of gaseous and liquid electrodes. (Manthiram et al. 2017)

Lithium-Sulphur

High energy density and cost reduction thanks to material abundance are the main drivers for the research in Lithium-Sulphur technology. The main technical issue with this technology is the "migration of intermediate soluble products which are transported from cathode to the Lithium metal anode where they react". Dendrite formation on the anode side is another problem which needs to be addressed. ((Manthiram et al. 2017; Ulissi 2017; Manthiram et al. 2014; Ould Ely et al. 2018)

Remark: dendrite formation is also a process in current LIBs which happens slowly and is responsible for the aging process of the battery.

The Lithium content for this technology is 0,41 kg/Wh. (Simon et al. 2015)

Lithium-Air

This battery technology is theoretically able to yield an exceptionally high energy density. One of the biggest issues are degradation processes in ambient atmosphere, and diffusion blockage by insoluble discharge products. These problems limit the reversibility (=> rechargeability) of the chemical process and the practical energy density of the battery. Many parts of the system still need to be improved until this technology is deployable. (Manthiram et al. 2017; Ulissi 2017)

The Lithium content for this technology is 0,14 kg/Wh. (Simon et al. 2015)

2.4. Expert Survey

The expert survey was conducted to get a sound opinion on the development of personal electric mobility in terms of the most promising technologies respectively chemistries, and furthermore to get an initial assessment on possible EV-shares for the future. The results are used to check the scenarios and to back up assumptions. In total 57 participants from all over the world took part, of which more than half indicated residence in Europe.

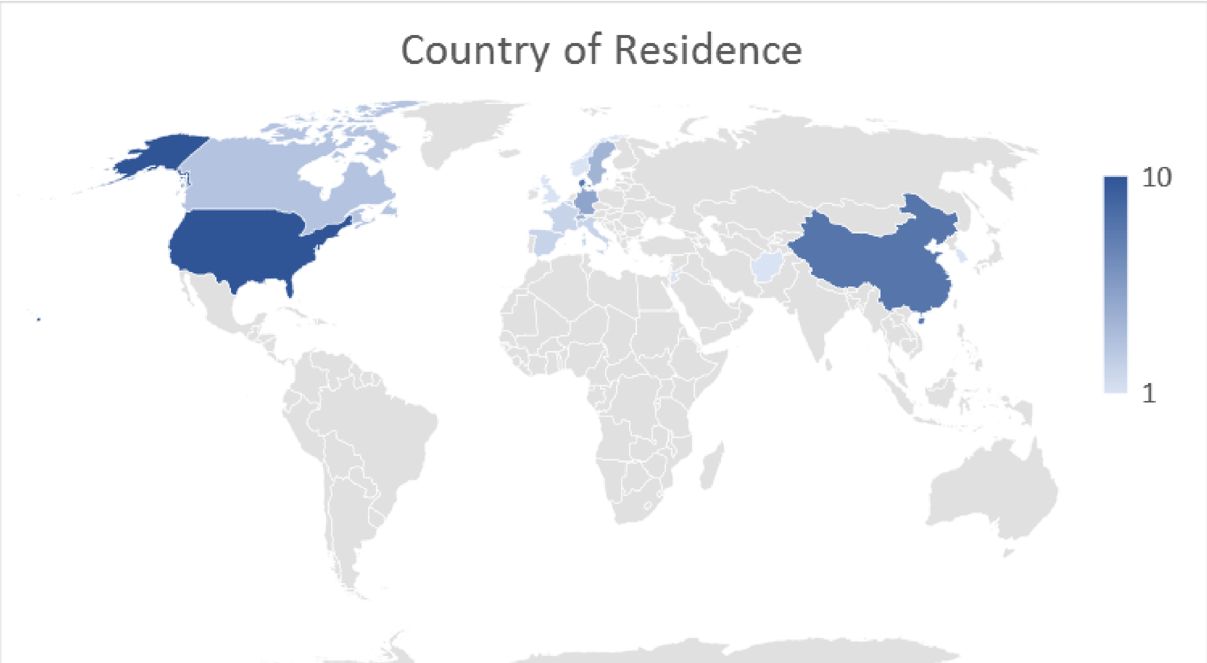


figure 5: survey participant's country of residence

56% of the participants came from Europe and the majority (42%) stated "professor" as their job title, 19% "researcher" and "scientist", 9% "postdoc" and 7% "engineer". The rest could not be assigned to one of the categories.

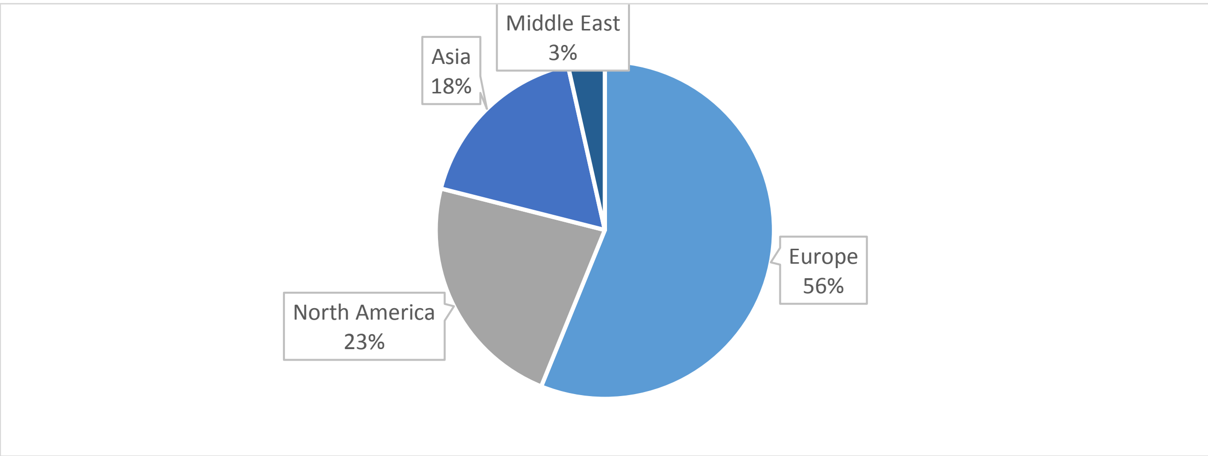


figure 6: survey participant's region of residence

The first question was posed to validate that experts see battery powered vehicles (BEVs) as the future alternative to ICEs. The results do not imply, that combustion technology will be phased out by 2030. When the answers are filtered per country, EU resident's answers are shifted slightly from BEVs (56%) towards Plug-in Hybrid Electric Vehicles (PHEVs). One participant remarked that due to EU regulations on fleet average CO2-emissions, all new vehicles would need to be electrified, classifying them as HEVs. The *Volkswagen AG* (23,9% market share in Europe in 2017) for instance plan to electrify their fleet by 2030. The *PSA Group* (16% market-share in 2017) is even more ambitious to reach the same goal by 2025. (Volkswagen AG 9/11/2017; PSA Group September 2018)

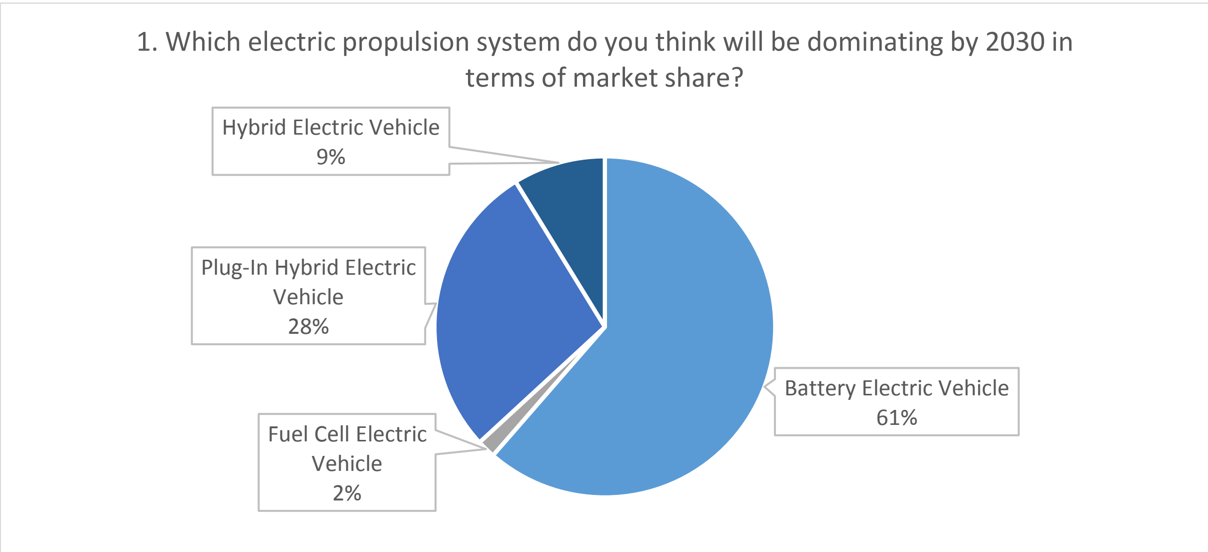


figure 7: participant's opinion on dominating technology by 2030

The selection of chemistries below did not just include LIBs, but also other alternatives beyond, which describe completely different technology paths. It was remarked, that selection option stands in contrast with the specific differentiation of listed NMC-chemistries and other state-of-the-art LIBs. The chemistries with the lowest Cobalt content and the currently highest energy density(-potential) ranked first and second, which strengthens the scenario's assumptions and is in line with literature data.

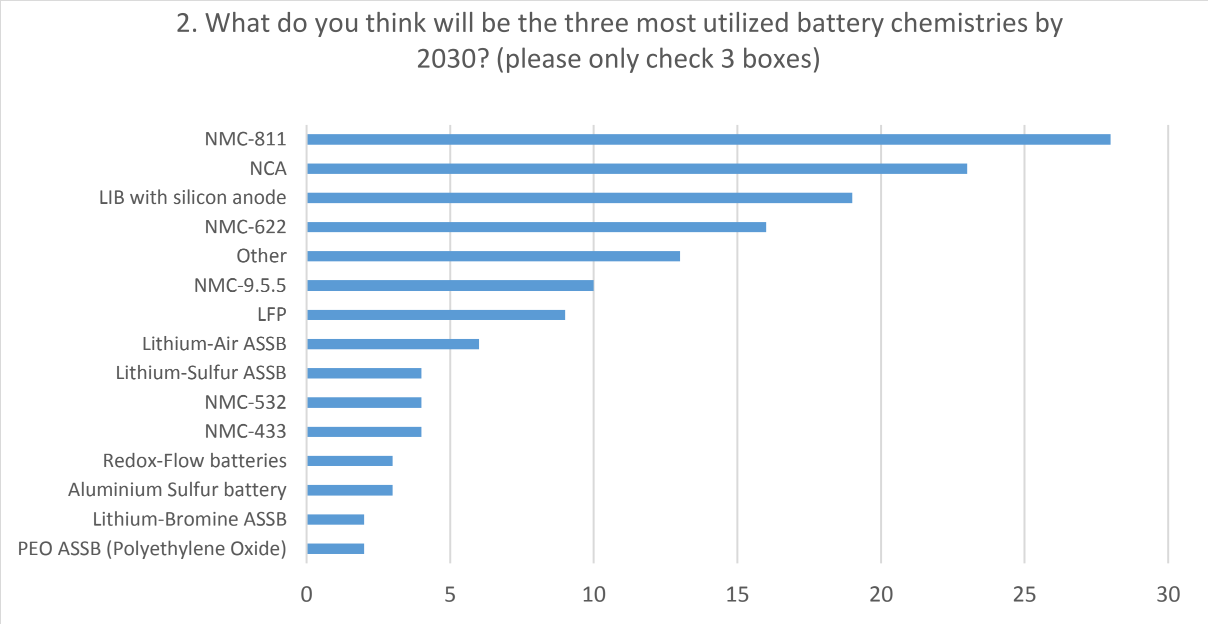


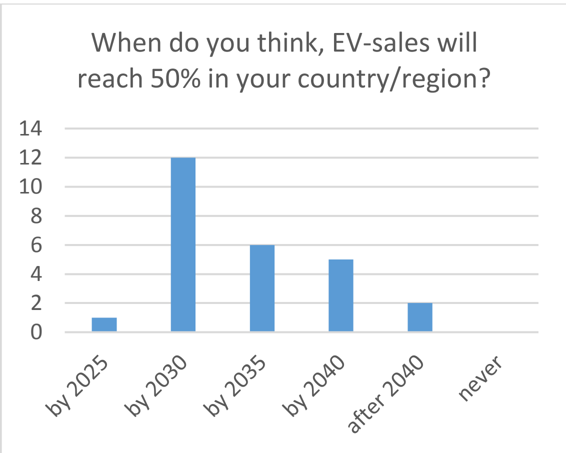
figure 8: participant's opinion on most utilised battery chemistry by 2030

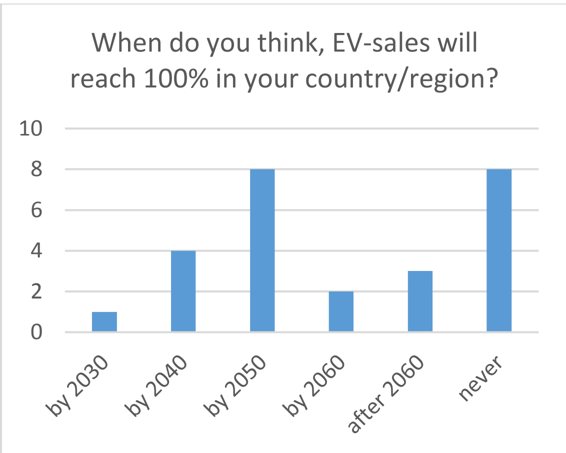
In the third question, participants were asked to rank the following challenges faced by battery technology to penetrate mass markets in personal vehicles from highest to lowest. The list below represents the ranking:

1. Cost
2. Charging Time
3. Capacity for Competitive Range
4. Charging Infrastructure
5. Cycle Life
6. Stability (Thermal, Chemical and Mechanical)
7. Energy Network Capacity
8. Material Criticality

The answers with the least deviation were, that cost is the biggest challenge for the development of battery technology, while energy network capacity and material criticality were clearly rated as a little challenge.

Furthermore, the participants were asked about their opinion on EV market penetration. The following figures include only answers from EU residents.





The estimates for the 50% EV-share are roughly in line with the scenarios 1 and 2. Whilst a significant share of participants from the EU does not believe, that a 100% market penetration will happen, the EU's goal of 30% EV-share by 2030 is rated as realistic according to the expert's answers in the graph above.

2.5. Scenario Assumptions

For the projection of the demand on Cobalt and Lithium, some basic assumptions are necessary for the relating calculations performed in the scenarios which are specified in the following sections below. The underlying data for all three scenarios is the same up to 2020. From there on, different developments are assumed. Battery technology - as the EV's energy storage - is expected to be the dominating propulsion system for all scenarios, as is the average energy consumption which is calculated as follows:

The vehicle segment shares from 2017 by the International Council of Clean Transportation (ICCT) are divided into three car groups which are assigned with a realistic energy consumption per vehicle class, based on data from *Fraunhofer Institut* (Wietschel et al. 2019):

	Market share	Energy consumption
Small (Mini, Small and lower Medium):	56%	14,7 kWh/100 km
Medium (Medium and upper Medium):	10%	17,3 kWh/100 km
Luxury (Luxury, Sport and SUV):	43%	24,0 kWh/100 km
Average:	100%	**18,1 kWh/100 km**

Derived from the average fleet consumption, a battery capacity of 90,5 kWh -108,6 kWh is needed to provide a range of 500 km to 600 km which is widely stated as being "competitive in comparison with ICE vehicles. The efficiency of the electric motor is already high and is not expected to undergo a drastic efficiency increase. The capacity influences the dimensions of the battery module as well as the price and is therefore seen as being restricted to a certain point depending on the technology in question (scenario 1, 2 or 3). A further assumption is applied concerning the integration of battery technology with a higher energy density: Development in this field will first lead to an increase of overall capacity before reducing the material demand per vehicle. This phenomenon is called "Jevons paradox" and can be observed in ICE technology as well. The expected battery capacities are presented in figure 10. The term "EV" includes Plug-in Hybrid Electric Vehicles (PHEV), which are usually equipped with batteries of capacities ranging around 5-17 kWh. With the current share of PHEVs in EVs the average battery capacity would be decreased drastically. This case is covered with the sensivity analysis in section 4. Partly lower incentives for PHEVs along with increased range of BEVs and the expert's opinion on the BEV as the dominant technology (section 2.4) contribute to the assumption of low PHEV shares for the future.

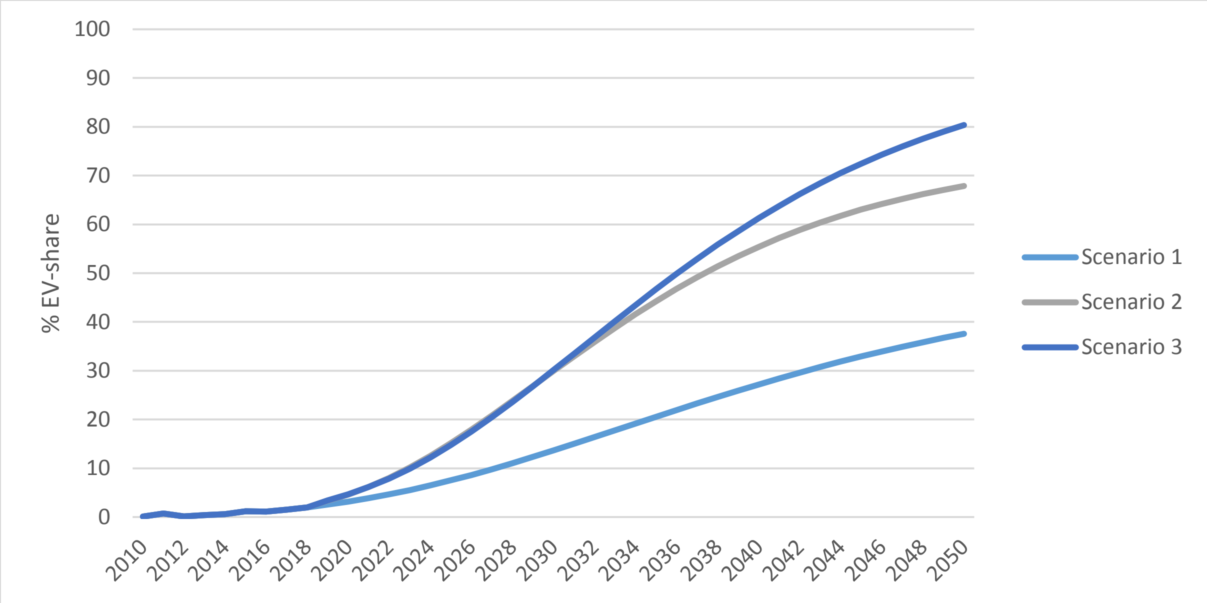


figure 9: EU EV-share, all scenarios

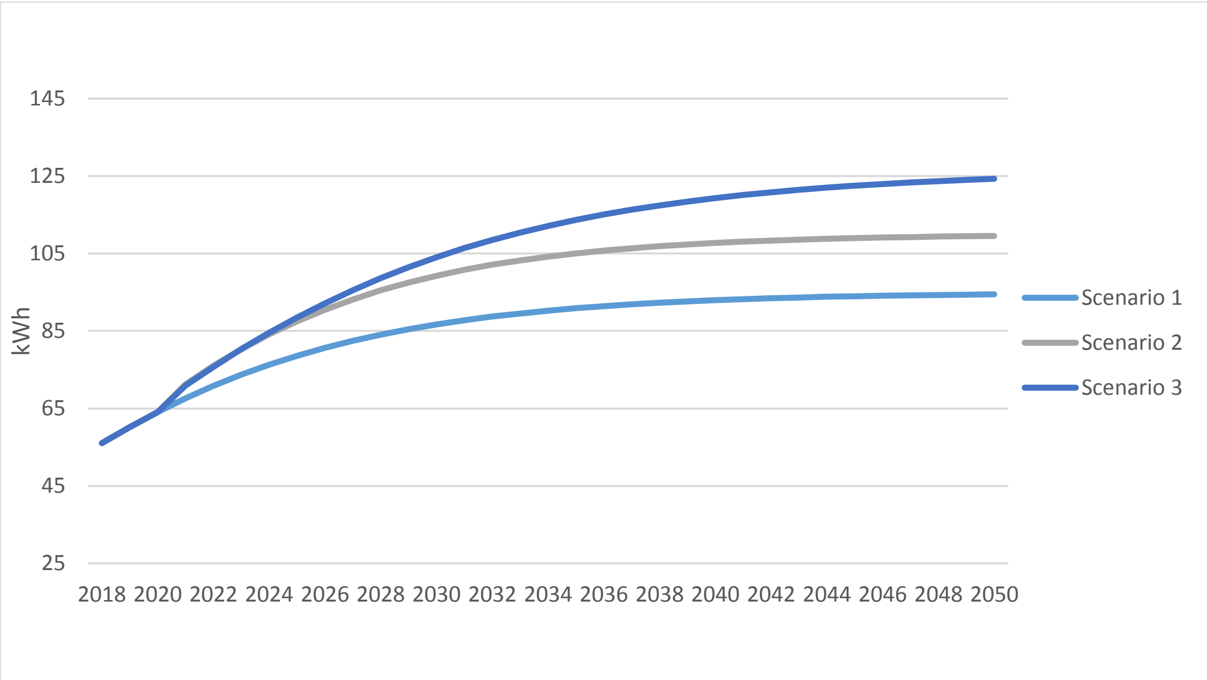


figure 10: average battery capacity per scenario

All scenarios are built on the basis, that the EV-market is growing. The pace and strength of the development rates differs in the scenarios according to the considered aggression of goals and incentive creation. The share curves are illustrated in figure 9. The following sections describe and reason the underlying data and assumptions for each of the scenarios.

Remark: The goodness of fit is not provided for the models, as they are all high due to the little number of data points they are fitted to.

2.5.1. Scenario 1

The incentives and technical attractivity for EVs as of today are assumed to stay the same. The steps towards competitive range and affordability are achieved with economies of scale, but Li-ion technology is the prevalent technology with the chemistry share development as projected in figure

11. The battery generation isn't going to develop beyond "generation 3a". Also, the relating limits for the average battery capacity are set at on an average of 95 kWh (restricted by weight, size and price). The interpolation based on the Gompertz model is manually restricted with a saturation level of 50% market share (*a* = 50). The future LIB-projection (figure 11) is based on estimates by *McKinsey Basic Material Institute*, *Darton Commodities Limited* and the *International Energy Agency (Azevedo et al. 2018; Darton Commodities Limited 2019; IEA Publications 2017)*. Their reports provided discrete estimations for certain years, of which a reasonable average was taken, and the years in between were interpolated. The two main cell compositions with the highest energy density and potential for Cobalt reduction are NCA and NMC, of which the NMC-811 will carry through. 49% of the survey's participants believe so as well (figure 8). The slow phasing-out of NMC-622 respectively NMC-532 is justified with a higher Research & Development effort necessary for the less stable NMC-811, which is why it would be first applied in higher class vehicles. The LMO and LFP technologies are displayed together as they both don't contain any Cobalt. Because of lower cost and high safety (LFP)or power (LMO), a niche market is assumed to stay for that type of LIB.

The contents of Cobalt and Lithium for the different cell chemistries can be accessed in section 2.1. The development of the per vehicle utilisation is displayed in figure 12.

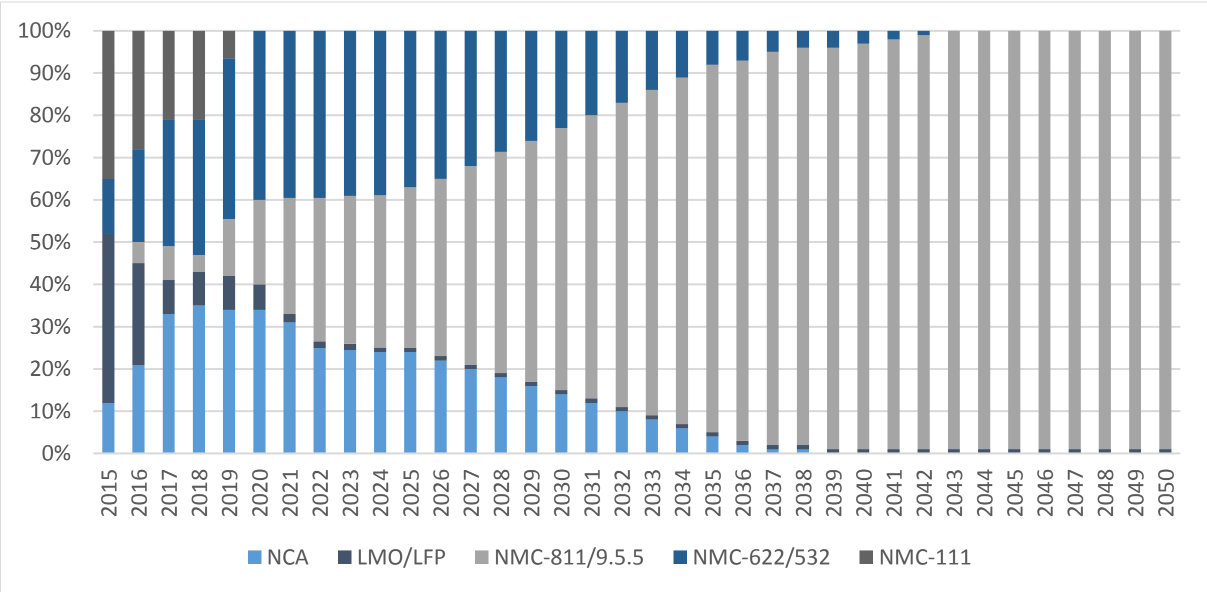


figure 11: battery chemistry development

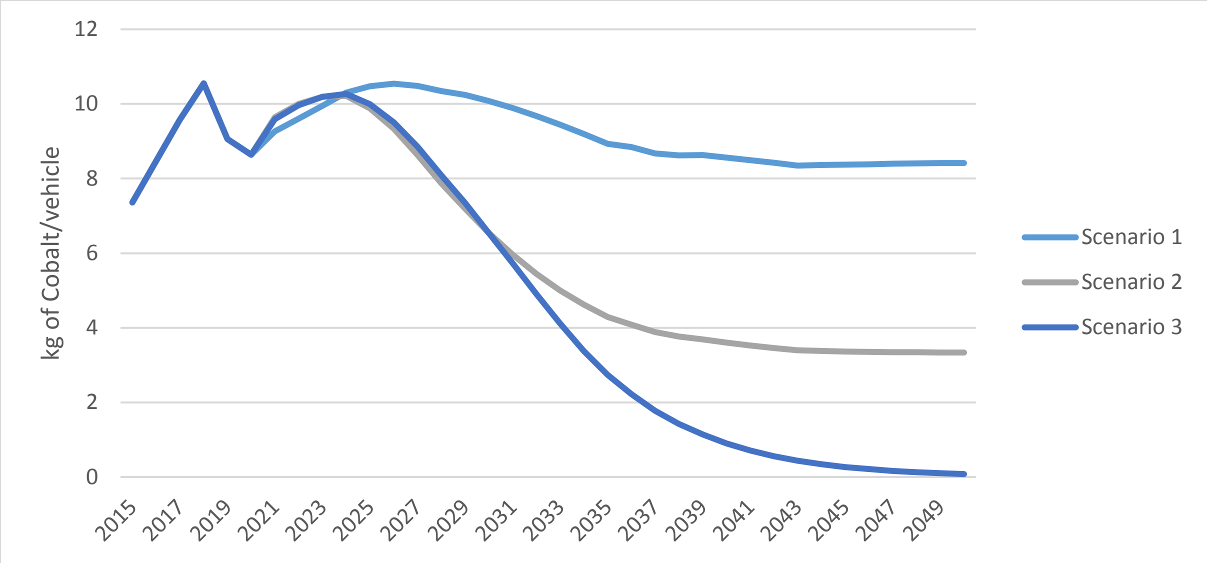


figure 12: average Cobalt use per vehicle projection

2.5.2. Scenario 2

For this scenario the EU's goal of 30% EV-market share in 2030 is expected to be reached. According to the ACEA this translates to 50% EV-share for the top 5 countries to balance the slower development of economically less powerful countries (ACEA 2018). The EV-market projection is individually modelled per country. The 50% scenario is independently modelled and should not be coupled with that of the EU, as the EU model already includes the five mentioned countries. The Gompertz curve for his scenario is forced through the points of 30% market share at 2030, respectively 50%. The saturation is restricted at 75% (see figure 9 – grey curve). The battery technology makes a step forwards in terms of price and performance with a gradual introduction of silicon anodes from 2022 on and improvements in cathode technology (HVS and HE-NMC, see section 2.1). The technology evolvement of the so-called generation 3b enables higher energy densities of up to 350 Wh/kg (Meeus 2018) and therefore increased range options 600km+ (battery capacities of around 110 kWh). The basic chemistry is unaltered. The Cobalt content saving potential arises from the energy density improvements, resulting in lesser material demand per watt-hour (see figure 12). The technology projection from Scenario 1 is gradually overlapped with the performance increase inhering from generation 3b gains.

2.5.3. Scenario 3

Legislation from the EU are constantly revised and intensified. Battery technology is seen undoubtably as the best propulsion system for personal vehicles. CO2 goals and EV-shares (from Scenario 2) are confidently reached. The saturation for the EV-market share prediction is set at 95% as some countries already announced the ban on fossil fuel cars (France by 2040, Netherlands by 2030, Denmark by 2030, UK by 2040, Sweden by 2030) (France set to ban sale of petrol and diesel vehicles by 2040 2017; Nielson 10/2/2018; Asthana and Taylor 2017). The most outstanding difference of this scenario though, is a breakthrough in battery technology, which allows again for higher battery capacities (up to 125 kWh) as energy density peaks at 750 Wh/kg (Meeus 2018).

The generation 4 battery technology (see section 2.3.3) makes personal transport with EVs the most comfortable and the cheapest option, boosting the market share drastically. The dependency on Cobalt for cathode technology is no decreasing due to the development of solid-state electrolytes and market ready Li/S_8, respectively Li/Air battery technology. The leap is explained in detail in section 2.3.3. Although Cobalt is not needed for this technology, Lithium metal is needed for generation 4, increasing the Li-demand per vehicle and thus per country drastically. The effects of this introduction are visualized in figure 13. The introduction starts in the early 2030s and substitutes the conventional LIBs from Scenario 1 and Scenario 2.

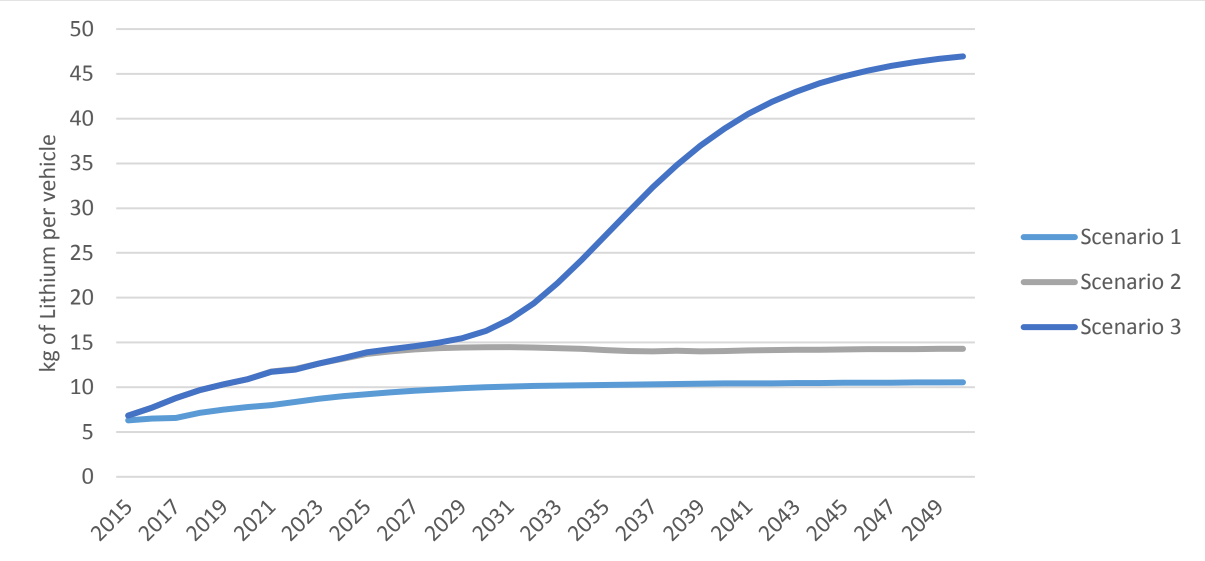


figure 13: average Lithium use per vehicle projection

3. Results

In the following, the inflows and outflows of Cobalt and Lithium are presented, calculated with vehicle ownership data from the MFA model, assumed EV-shares, corresponding average battery sizes and average battery technologies with the relating shares of Cobalt and Lithium per kilowatt-hour.

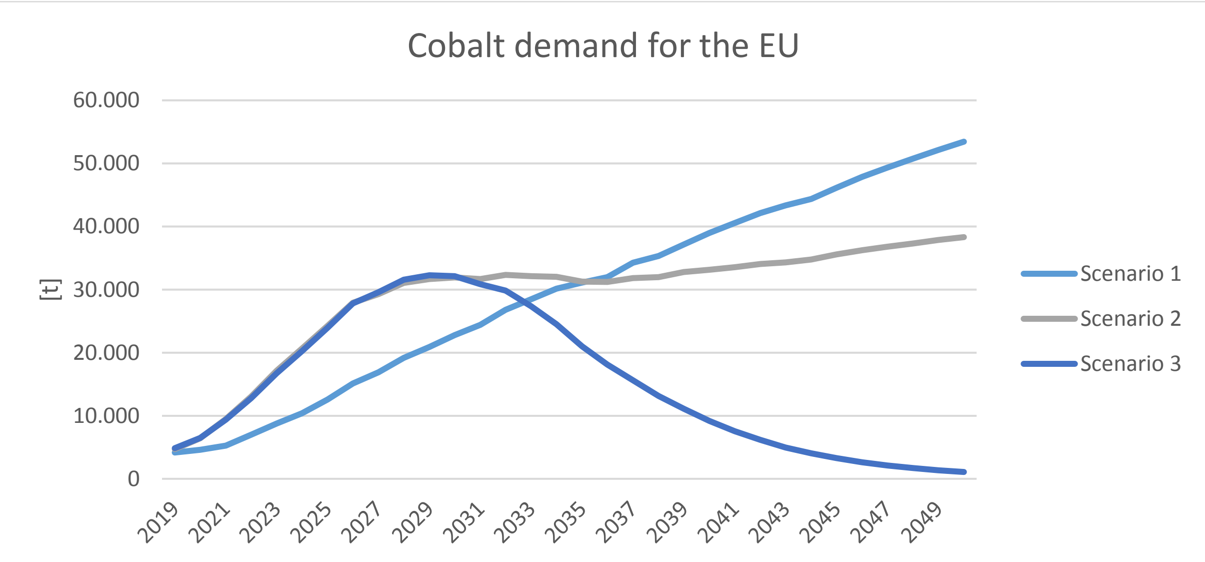


figure 14: Cobalt demand projection for the EU

The Cobalt demand from Scenario 1 increases almost linear from the year 2022 on. This can be explained with a high Cobalt content per vehicle in the years up to 2030 due to increased battery capacities, aiming to match the range of an ICE vehicle. Whilst the Cobalt content is high, the slower development of the EV-market counteracts the curve, resulting in a linear characteristic: figure 14 results from a multiplication of the data from figure 9 and figure 12. From 2030 on, the technology in scenario 1 saturates at a value of about 9 to 8,4 kg of Cobalt per vehicle (compare with figure 12). As this scenario assumes a moderate development of EVs, the market share increases steadily from 2030 onwards.

Scenario 2 demonstrates a much stronger increase in Cobalt demand due the technology developments described in section 2.3.2. The development enables an earlier increase in the overall battery capacity of the average passenger car, although the Cobalt needed per watt-hour decreases slightly. Only in around 2030, the technology is fully developed and deployed. The battery capacity is at a competitive level (meaning capacity enables ranges up to 600km) and the material advantage per kWh results in an overall lower Cobalt demand (compared to scenario 1). The curve pitch after 2035 is related to the EV-market development.

Scenario 3 includes very similar influencing parameters up to 2030. From that point on the technology revolution (explained in section 2.3.3) shows its effect. Technologies with no, or little Cobalt content are utilised, leading to a drastic decrease in demand towards 2050.

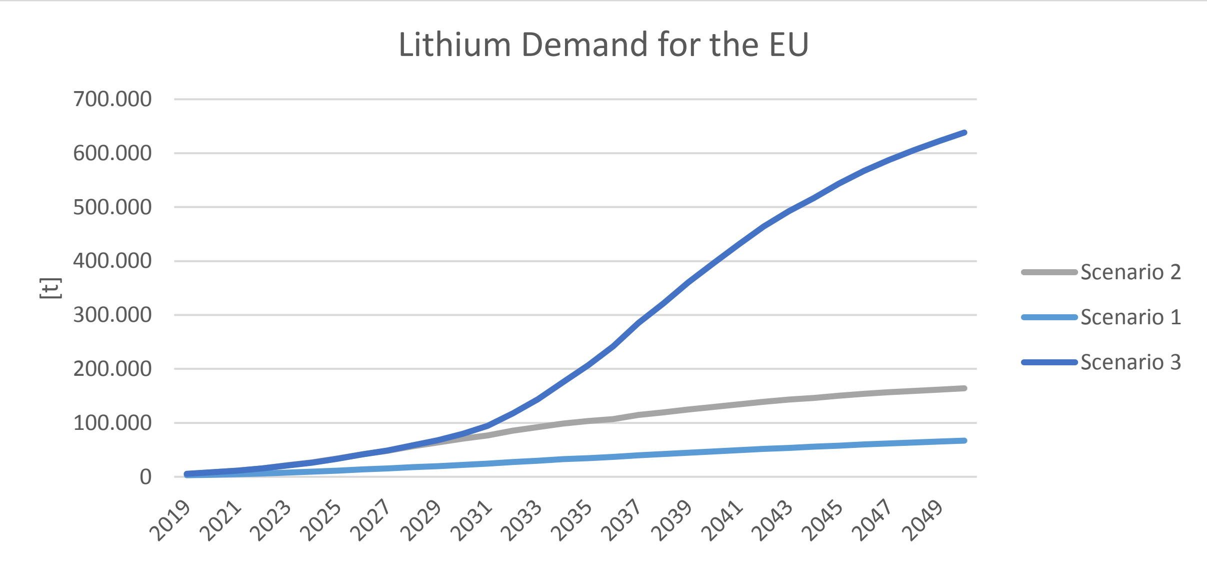


figure 15: Lithium demand projection for the EU

The development for the Lithium demand on the other hand (figure 15) has different characteristics. The main reason for this demand projection for the coming years is that all technological developments are dependent on the utilisation of Lithium due its superb material characteristics. The Lithium demand for all scenarios up to the year 2030 is gradually increasing as the average percentage in the battery technologies only varies slightly, thus EV-share and average battery capacity are the main demand drivers up to that year.

The Lithium demand in scenario 1 has a similarly linear shape like the Cobalt demand (figure 14), which is for the same reason: slow EV-development until 2030, which is equalled out by increased average battery capacity and a steady development from that point on.

The higher Lithium demand development for Scenario 2 is due to the higher average battery capacity and overall increased demand.

The technology revolution starting from 2030 for scenario 3 can be explained by the utilisation of Lithium metal as an anode material which drastically increases the Lithium content per kWh. (see Lithium-Sulphur)

The results for Germany, the United Kingdom, France, Italy and Spain have an overall more drastic increase for Scenario 2 and Scenario 3 due to the need for the assumed necessity of balancing out a possibly slower EV-development in other EU-member countries – with a resulting EV-share goal of 50% in 2030. This assumption leads to the projection, that the accelerated EV-demand in these five countries – which are accountable for around 70% of the vehicle market – peaks in 2030 at around 38.500t demand, which is 20% more than for the overall EU-scenarios. This is due to the same base technology development on which the scenarios are based on. In the years up to 2030 battery chemistries are still comparably Cobalt-rich. The shape of the curve has the same characteristics as the whole of the EU, as the main different parameter is the assumed EV-market share development. The two materials are included in one graph (figure 16).

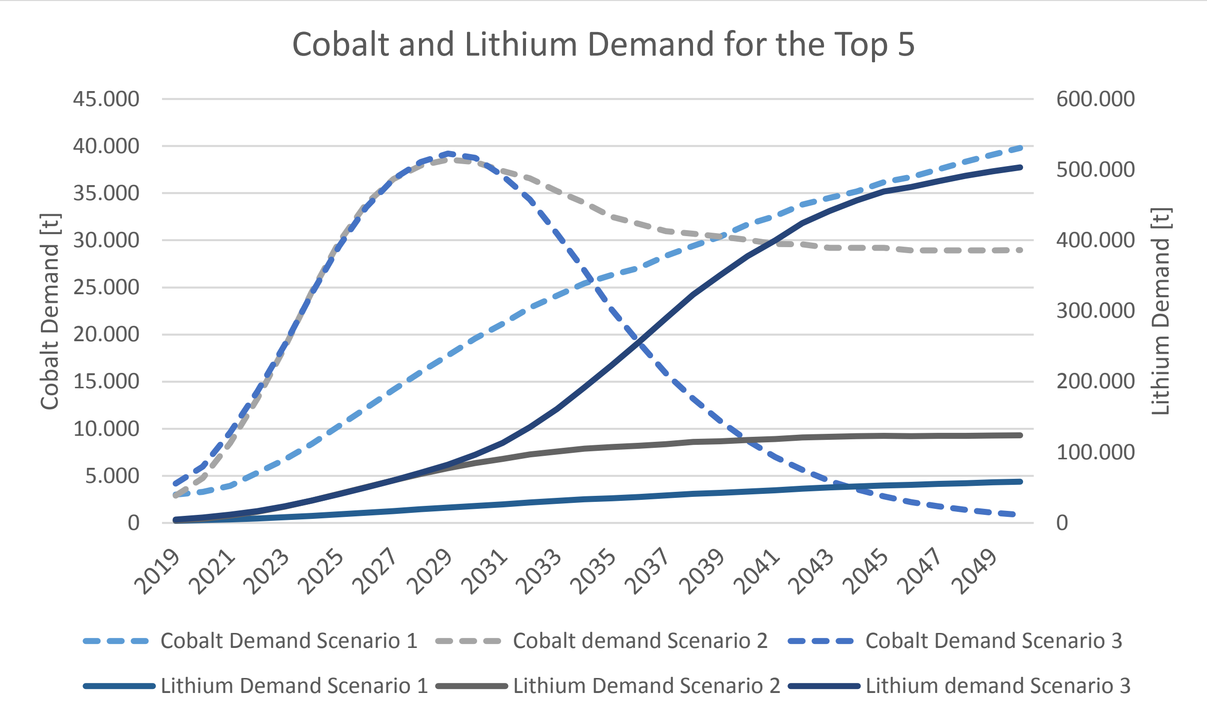


figure 16: Cobalt and Lithium Demand for the Top 5 countries

The dynamic MFA-model includes a fixed lifetime distribution per EU and for each individual country, leading to an outflow of material after the cars are retired. The plausibility of the selected lifetime is arguable for an EV, but a different lifetime is not considered in this thesis. A possibly shorter lifetime assumption for all passenger cars or just EVs would increase the overall demand for vehicles to sustain the stock, which would also boost the demand for the accessed materials here. The sensitivity of the lifetime is dealt with in the Sensitivity Analysis. The lifetime assumption also affects the outflow of material (retired cars). The following graphs (figure 17 and figure 18) presents these outflows of Cobalt and Lithium with the same assumed lifetime distribution (and other underlying data: Scenario Assumptions).

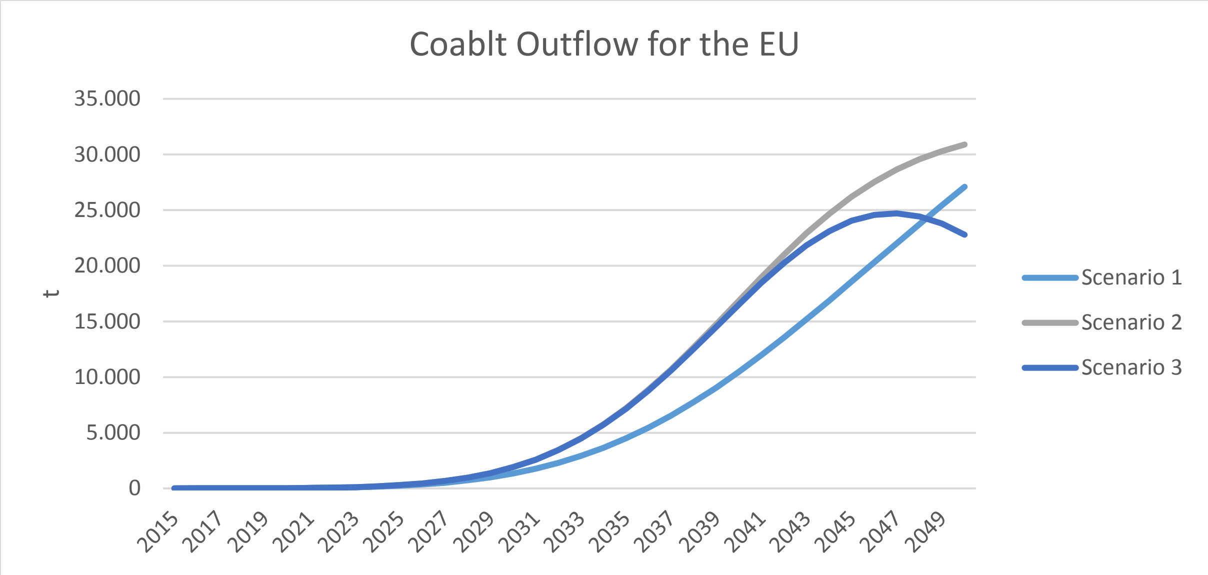


figure 17: Cobalt outflow for the EU

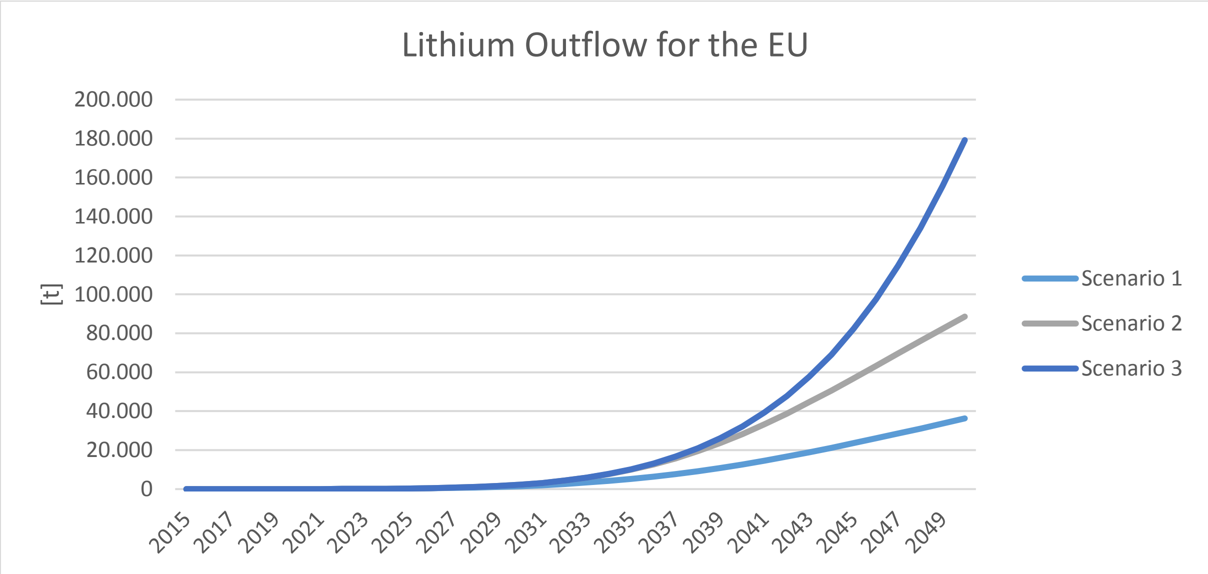


figure 18: Lithium outflow for the EU

The outflow of material could partly cover the demand, by recycling End-of-Life batteries. Cobalt is almost 100% recoverable while the recycling of Lithium is still in its infancy (Simon et al. 2015). These aspects are not considered in the following graphs which displays the decreased demand through recycling. These results can be interpreted as an upper potential limit for recycling.

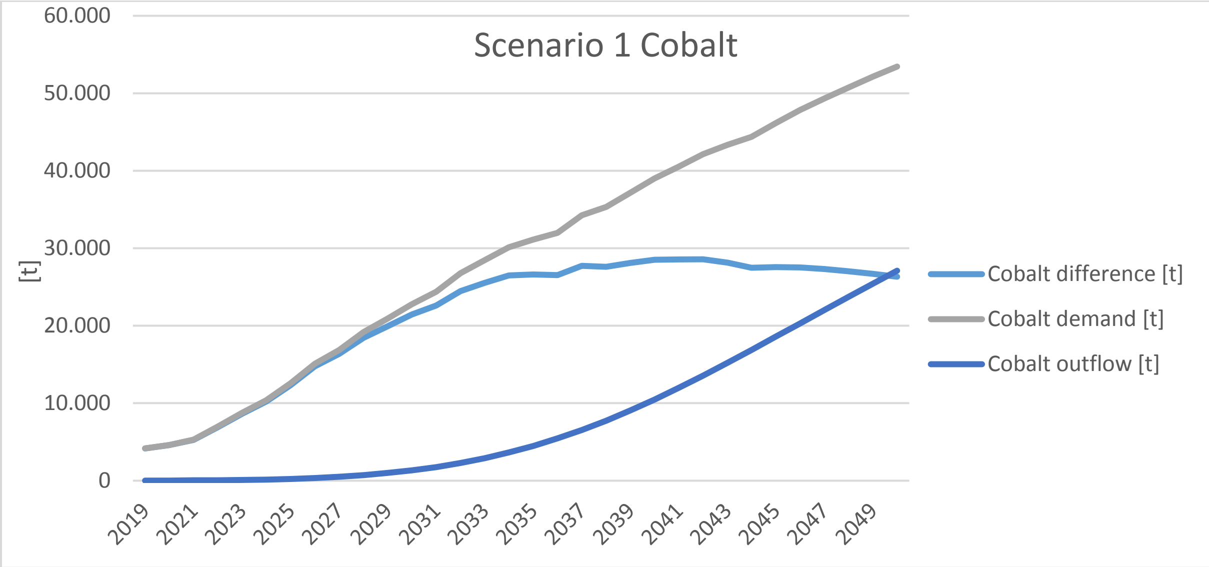


figure 19: Cobalt flows of scenario 1

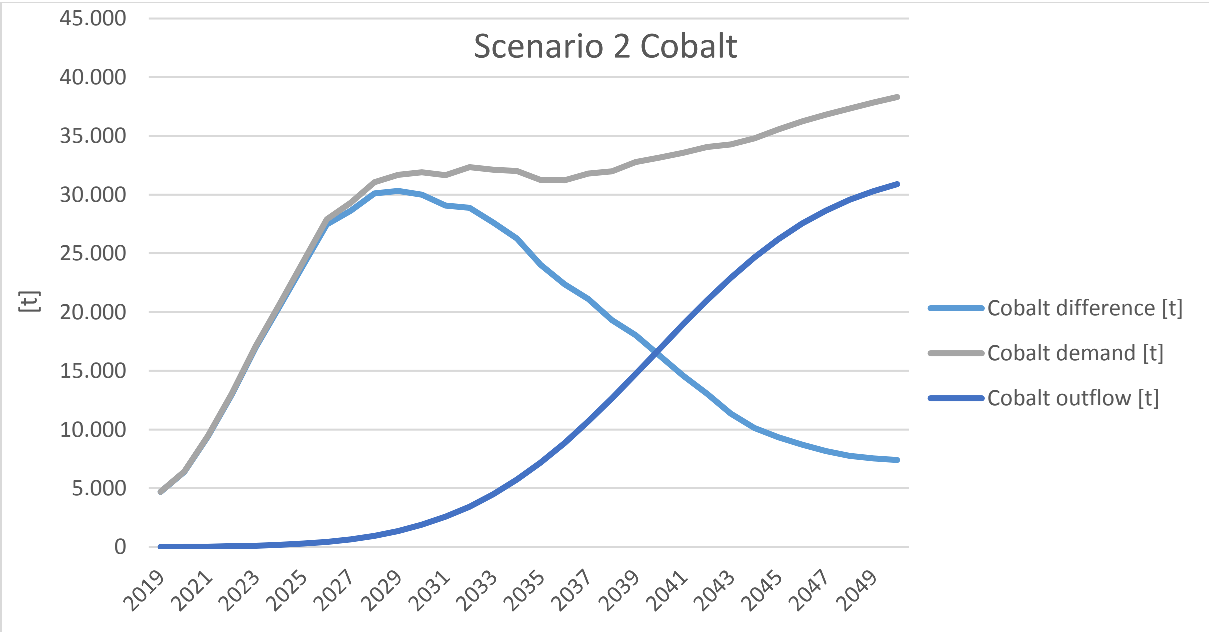


figure 20: Cobalt flows of scenario 2

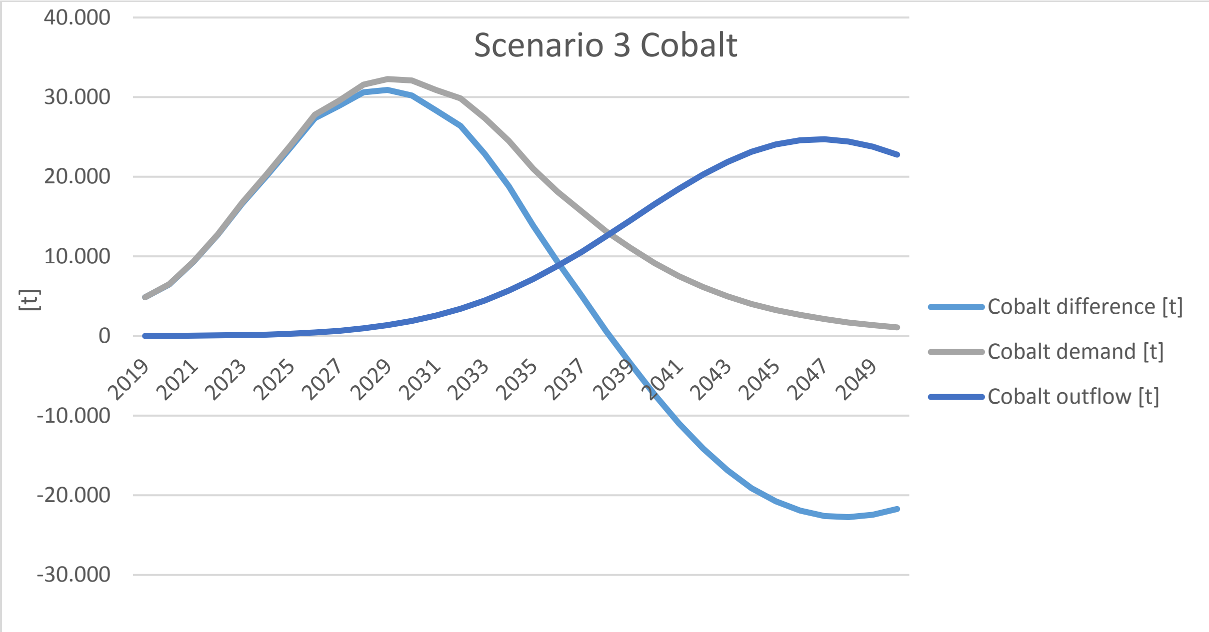


figure 21: Cobalt flows of scenario 3

Due to the linear development of the Cobalt demand in figure 19 one can see that from 2040 on, a certain percentage of demand is covered by cohorts leaving the stock. In figure 20 the strong Cobalt demand from the start of the development (2020-2030) covers a bigger share than in scenario 1 and subsequently decreasing the demand which would elsewise be needed. In figure 21, the outflow is bigger than the demand due to the low Cobalt percentages used in vehicles.

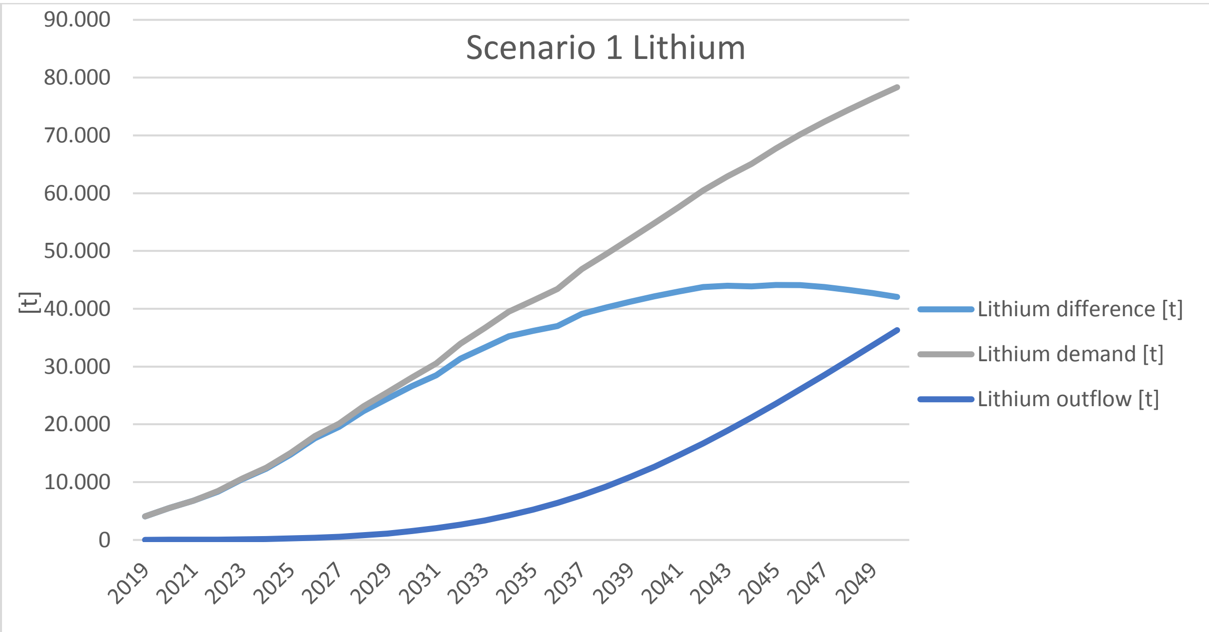


figure 22: Lithium flows of Scenario 1

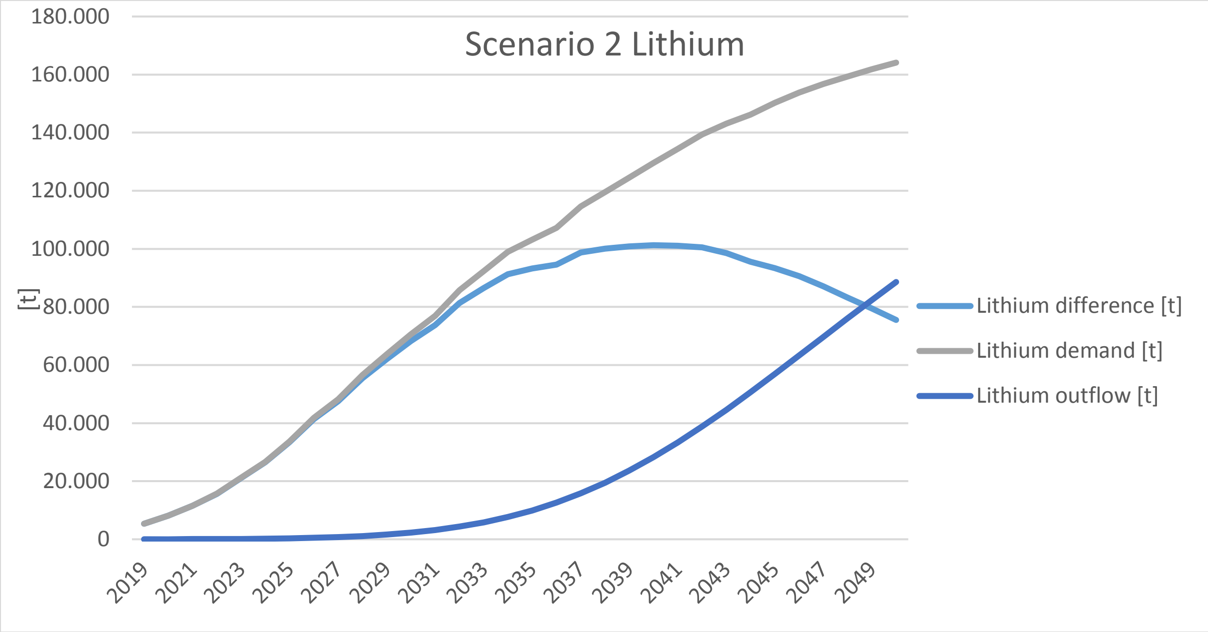


figure 23: Lithium flows of scenario 2

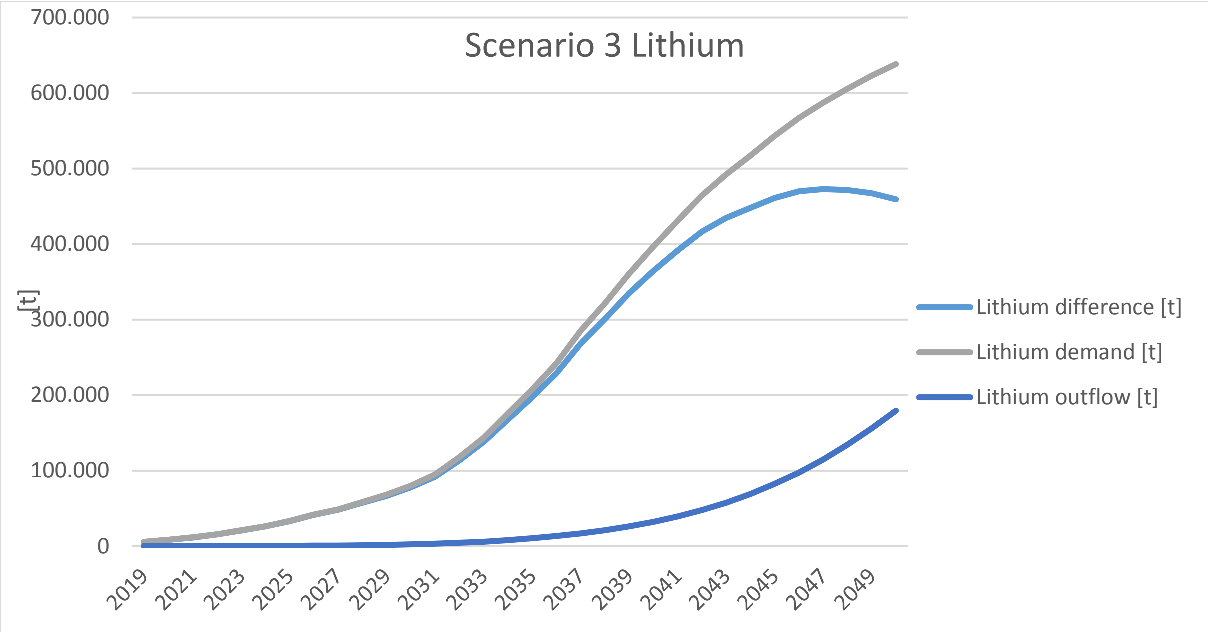


figure 24: Lithium flows of scenario 3

The Lithium in- and outflows (figure 22, figure 23 and figure 24) inhere the same characteristic shape. The Lithium outflows never cover the demand as this material is not intended to be substituted so far.

4. Sensitivity Analysis

This section tests the percentual effects of influencing parameters on the results, namely:

- Vehicle lifetime: This parameter is set constant from the years 1960-2050 which inheres potential to project wrong developments. In this study, the main influence of this parameter is the demand for new vehicles. Based on the EU, whose average lifetime is assumed to be 17 years, with a standard deviation of 5 years (based on the comparison of modelled vehicle demand with projected demand), a lifetime of 14 years and 20 years with the same standard deviation is calculated and compared. A higher demand is directly linked to the cobalt and

Lithium demand in a certain year, as the other key parameters are not affected by vehicle demand:

- The shorter lifetime of 14 years would increase future demand by 20 %
- The longer lifetime of 20 years would decrease future demand by 15 %

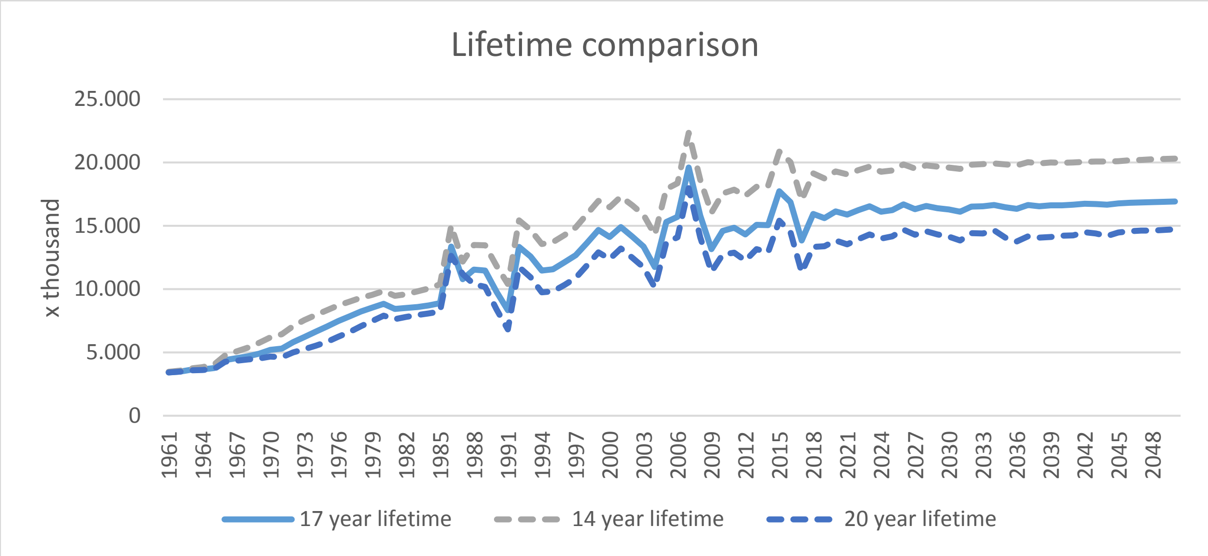


figure 25: Lifetime influence check

- Battery capacity: The capacity is indicated in kWh, while the demand for Cobalt and Lithium is stated in kg/kWh, a higher battery capacity subsequently means a higher material demand for a vehicle with the same battery technology, thus an increase or decrease in the average battery capacity leads to the same percentual in- or decrease in material needed. The share of the type of chemistry has a big uncertainty and is not covered in this section. The scenarios partly represent this part.
- Per capita vehicle ownership: This parameter is put together by dividing the number of registered vehicles (stock) by the population for the related are for the same year. The analysis of this parameter therefore also covers future stock and population. The number of vehicles per capita for the EU model used here is 548 in 2050. To test the sensitivity the number for 2050 is altered and linearly interpolated from 2015.
    - 600 vehicles per 1000 capita would finally lead to 13% increase in demand
    - 500 vehicles per 1000 capita would finally lead to 10% decrease in demand

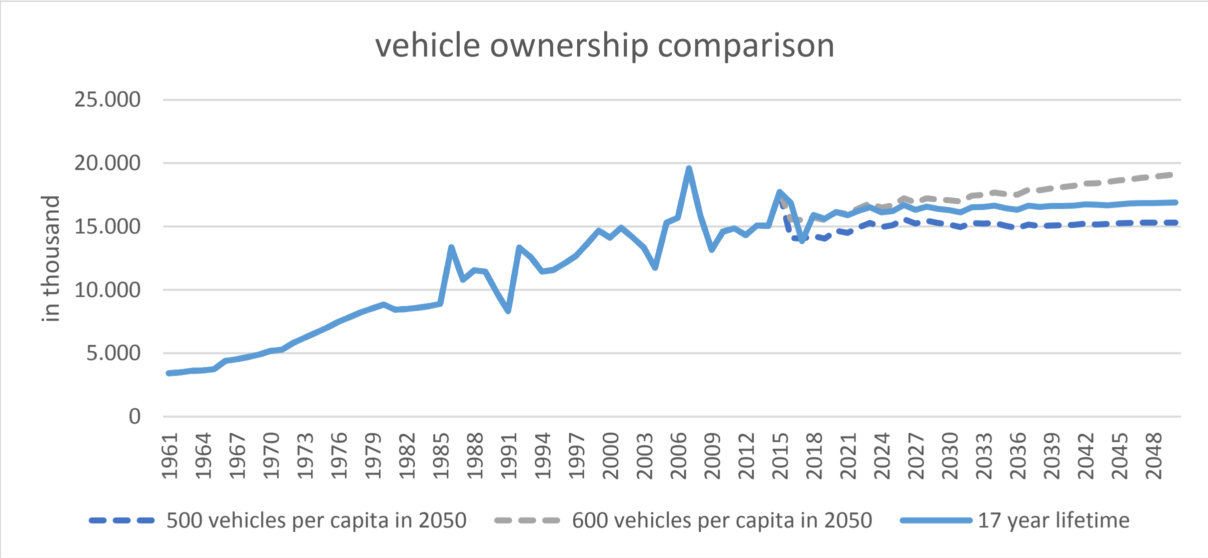


figure 26: vehicle ownership influence check

5. Discussion

Obviously, the demand for Cobalt and Lithium in the sector of electric mobility is mainly driven by the Wh-demand of installed batteries. The potential progress in terms of energy density and cost reductions demonstrated by the technology steps in the three scenarios is tremendous - the technology of battery generations beyond conventional LIBs is particularly promising. The calculated material flows in this study bear considerable uncertainties due to the temporal scope of the projections but also due to the current development stage of the EV market; market shares are just starting to reach figures above 1%. The concerns about material supply shortages could be diminished in the coming decade, provided the technology evolves according to the described technology steps. (section 2.3). This study only provides possible demand scenarios for Cobalt and Lithium and analyses the potential for recycling. The scenario assumptions and the resulting projections overlap with some of the existing literature. A selection of which is listed below:

- *Cobalt Market Review 2018-2019* (Darton Commodities Limited 2019): The scope of this market review covers the wold. The projected EV-shares up to the year 2025 equal those assumed in the scenarios here.
- *Lithium and Cobalt – A Tale of Two Commodities* (Azevedo et al. 2018): This report covers projections for the world but the growth factors until 2025 are in the same range. The Cobalt demand projections in this study are estimated to be higher (only for the more optimistic scenario 2 and 3)
- *Global EV Outlook 2018* (IEA Publications 2017): The projections of the future EV market are similar up to the year 2030.
- *Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe* (Simon et al. 2015): In this slightly older report, the characteristics of the Cobalt and Lithium demand curves resemble with those in this report. The assumption of the breakthrough of Lithium-Sulphur is assumed to start from 2025 onwards. The effect of that technology (scenario 3) comes only into effect in 2030 for this study

The demand projection in this study is restricted to passenger cars. It does not account for battery uses in other vehicles such as 2-wheelers, vans, lorries, planes or ships. These transport sectors withhold sizeable potentials for the application of battery technology. Battery-electric ferries are already in use und small passenger airplanes for short trips up to 100km are under development

Cobalt is not only needed in the production for LIBs. The list below shows the end use of other important applications for Cobalt with their percentage form 2018. The shares are expected to grow but the demand for LIBs has by far the highest rate of increase with 9,4% (Darton Commodities Limited 2019):

- Battery chemicals: 54%
- Superalloys: 16% - used for instance in turbines and medical prosthetics
- Hard metals: 7% - used for instance for cutting tools, mining, oil & gas drilling,
- Catalysts: 5% - used for instance for oxidation (polymer production) and in gas and oil refining processes
- Pigments: 5% - ceramic and glass colouring applications

While often assumed to be similar, battery lifetime and vehicle lifetime are not necessarily congruent for BEVs. Currently, most manufacturers offer 8 years or 160.000km (100.000 miles) of warranty on their battery packs (Office of Energy Efficiency & Renewable Energy 2/22/2016). The end of a battery's lifetime is - by most assumptions - reached, when less than 80% of the original capacity is left, which does not mean that the battery has reached the End-of-Life (EoL) (Olivetti et al. 2017). As an EVs motor is less complex than an ICE due to the smaller amount of moving parts, the EV's life is possibly longer than its containing battery pack. The assumption of utilising more than one battery pack per EV would increase the projected demand of related materials.

Used batteries from EVs which have not yet reached their EoL can contribute with an extended service in stationary applications, to improve grid stability (Parkinson 2019), or provide energy storage in residential areas to store energy from solar panels (Lu et al. 2017).

In terms of the projection technique applied in this study, some limitations need highlighting: The use of the Gompertz curve is a reasonable approach when enough data is available. The EV-shares, which were extrapolated consisted of percentage numbers of less than 3% and 9 data points, representing yearly averages. With this initial stage of development, the Gompertz curve could cause uncertainties in the long-term projections. Taking Spain and Italy as an example: due to the low EV-shares, the growth curves of these countries are much steeper. The development of the EV-market in the last 10 years forces the projection of these countries on to the same scale and timeframe which results in quicker market saturation compared with other countries. This result is misleading, it merely shows that Italy and Spain need to catch up with the market development in order to meet the EU's goals for 2030.

The meaningfulness of this study would improve with a more extensive base-data set of the EV-market development. With higher sales shares and matured battery technologies, an MFA model based on EV stock - rather than deriving demand from total vehicle stock - would be a more reasonable approach to project future demand for EVs. After the first age cohorts leave the stock, the lifetime assessment of EVs and their future projections would result in a sounder model, thus a retake of this model in a few years' time would be sensible.

Remark: Literature and the conducted survey suggest, that the Nickel-rich NMC-811 chemistry will become the dominating LIB technology in the coming decade. With 0,094 kg/kWh of Cobalt content, this type of battery would use little more than the next generation of NCA technology (4g/kWh), which is utilised in Tesla's Model 3. The energy density of that BEV is also the highest on the market so far, which bears the question, why the NMC-811 would be the choice of technology, when the promised energy density is in the range of the second generation of NCA. In the beginning of 2019, a small start-

up called e.GO started selling their BEVs, which are placed in the small city car section. On the question of their utilised cathode chemistry, the company replied, that they chose NCA technology. During the research of this thesis and constantly new appearing announcements and articles, the author could not understand, why NCA technology is widely assumed to phase out in the coming decade.

6. Conclusion

The upcoming material demand for EV-batteries induced by the authorities with aim of decarbonising transport by passenger car requires a different selection of materials for the producing stage of that sector. The battery demand and the related need for Cobalt and Lithium strongly influences the market of these elements. So far LIB demand was dominated by portable electronic devices; the LIB demand for EVs is estimated be many times over that in the future. The intensity of the demand-increase is most dependent on the development battery technology and the EV market. The three scenarios in this study highlight the importance of the overall battery capacity applied in an EV and the related relevance of sensible material use. Scenario 3 furthermore demonstrates the effect of a breakthrough with Cobalt free technology and strong increase in Lithium demand.

Acknowledgement

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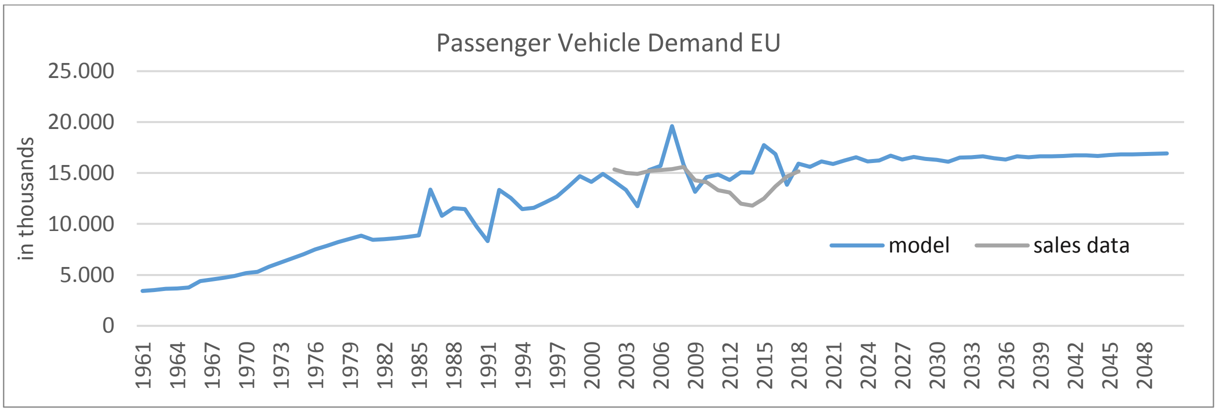
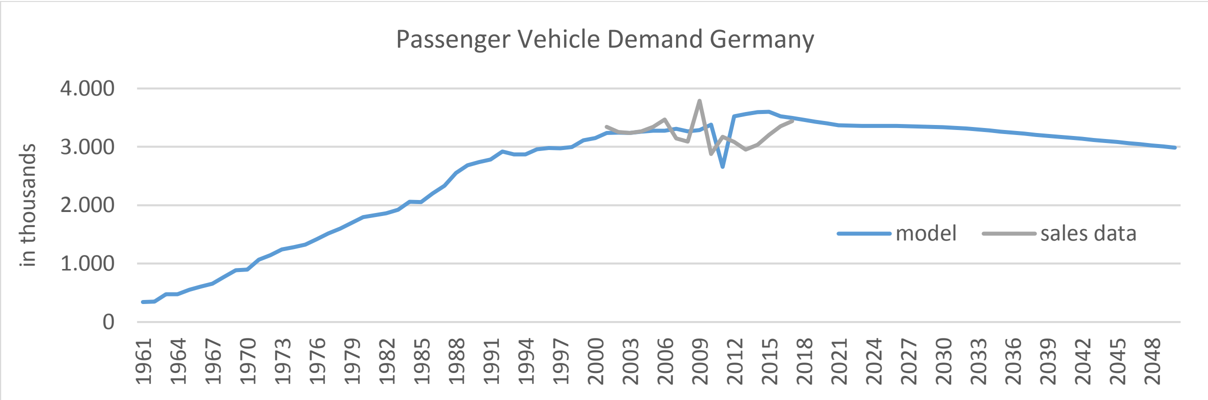
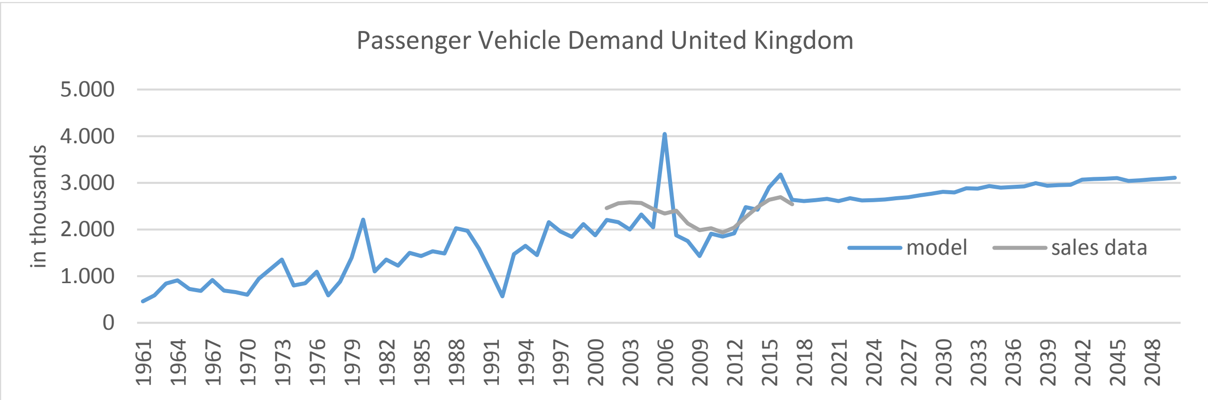
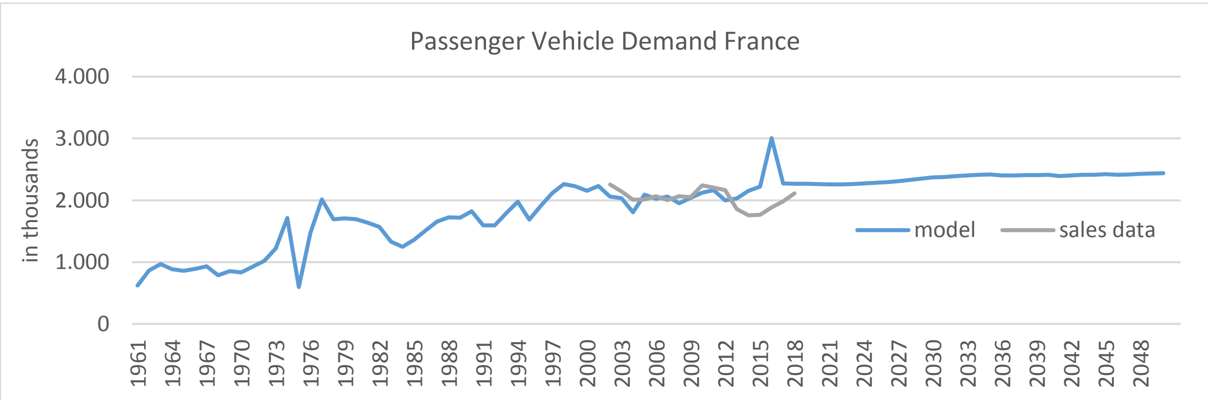
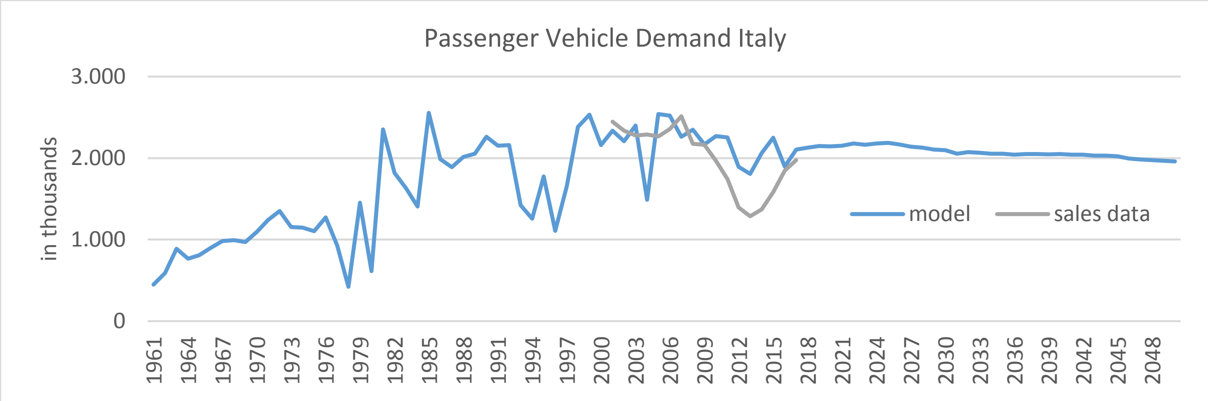
Appendix


Passenger Vehicle Demand EU
in thousands
25.000
20.000
15.000
10.000
5.000
0
model
sales data
1961 1964 1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021 2024 2027 2030 2033 2036 2039 2042 2045 2048


Passenger Vehicle Demand Germany
in thousands
4.000
3.000
2.000
1.000
0
model
sales data
1961 1964 1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021 2024 2027 2030 2033 2036 2039 2042 2045 2048


Passenger Vehicle Demand United Kingdom
in thousands
5.000
4.000
3.000
2.000
1.000
0
model
sales data
1961 1964 1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021 2024 2027 2030 2033 2036 2039 2042 2045 2048


Passenger Vehicle Demand France
in thousands
4.000
3.000
2.000
1.000
0
model
sales data
1961 1964 1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021 2024 2027 2030 2033 2036 2039 2042 2045 2048


Passenger Vehicle Demand Italy
3.000
2.000
1.000
0
in thousands
model
sales data
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
2018
2021
2024
2027
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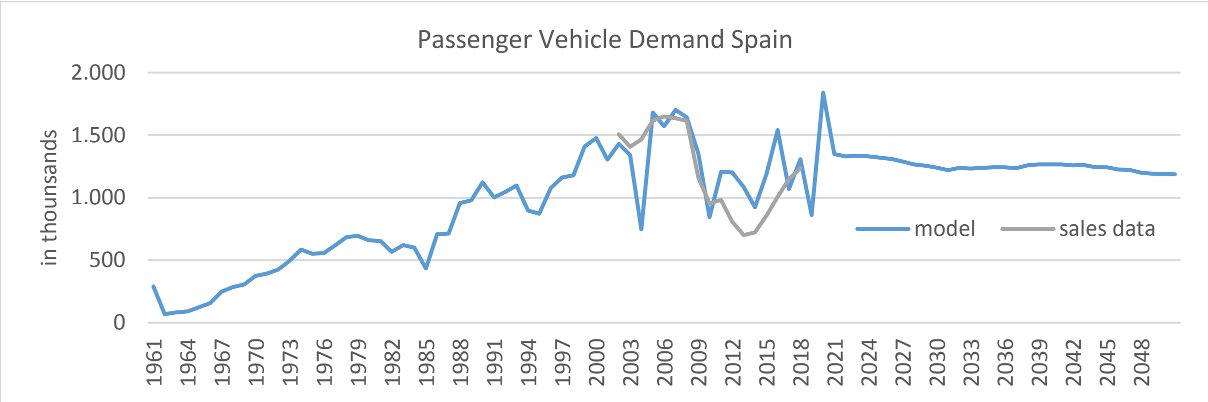
2036
2039
2042
2045
2048


Passenger Vehicle Demand Spain
2.000
1.500
1.000
500
0
in thousands
model
sales data
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
2018
2021
2024
2027
2030
2033
2036
2039
2042
2045
2048

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