FEDERATION INTERNATIONALE DE L'AUTOMOBILE
REGION I - EUROPE, THE MIDDLE EAST AND AFRICA

FIA Region I - Expert study on guidance and recommendations regarding electric vehicle propulsion battery end-of-life policies.

Image courtesy BMW

Study scope and methodology

This expert study focuses on batteries of electric passenger vehicles and their recyclability, re-use, and recoverability. The report is based on scientific literature, statistics, and public available evidence from research projects, as well as relevant legal requirements and technical standards. The scope of the report is limited to automotive lithium-ion batteries and excludes other parts of electrified vehicles; geographically, the focus is on Europe.

Underlying report has been commissioned by FIA Region I and the content has been gathered and written independently by Prof. dr. Maitane Berecibar and Prof. dr. Maarten Messagie, experts in battery technology and sustainability respectively.

08 November 2022

Version 2.03

Table of Contents

Glossary

AESC	Automotive Energy Supply Corporation
BCU	Battery Control Unit
BEV	Battery Electric Vehicle
BMS	Battery Management System
BMU	Battery Management Unit
BTMS	Battery Thermal Management System
CNG	Compressed Natural Gas
CAN	Controller Area Network
DAQ	Data Acquisition System
DoD	Depth of Discharge
EoL	End of Life
HEV	Hybrid Electric Vehicle
H_2	Hydrogen
LAM	Loss of Active Material
LCA	Life Cycle Assessment
LCO	Lithium Cobalt Oxide, $LiCoO_2$
LFP	Lithium Iron Phosphate, $LiFePO_4$
LIB	Lithium Ion Battery
LLI	Loss of Lithium Inventory
LMO	Lithium Manganese Oxide, $LiMn_2O_4$
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LTO	Lithium Titanite, $Li_4Ti_5O_{12}$
NCA	Lithium Nickel Cobalt Aluminium Oxide, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
NMC	Lithium Nickel Manganese Cobalt Oxide, $LiNi_xMn_yCo_zO_2$,
ORI	Ohmic Resistance Increase
PED	Primary Energy Demand
PEF	Product Environmental Footprints
PEFCR	Product Environmental Footprint Category Rules
PE	Polyethylene
PHEV	Plugin Hybrid Electric Vehicle
PP	Polypropylene
PV	Photovoltaic
PVDF	Polyvinylidene fluoride
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
SBR	Styrene butadiene rubber
SoC	State of Charge
SoE	State of Energy
SoH	State of Health
SoP	State of Power
SoS	State of Safety
SoX	State of X
ThMU	Thermal Management Systems

1. Executive summary

FIA Region I - Expert study on guidance and recommendations regarding electric vehicle propulsion battery end-of-life policies.

Chapter 2
The market share of battery electric vehicles and plugin electric vehicles is growing substantially since 2018 and had, in 2021, an average market share of 20% in EU 27. Although many cars have a battery capacity of 60kWh or more, there is no standard battery in electric vehicles; the commonly used battery cells have different cathode material compositions and types of formats. The design of the battery pack is unique to each car manufacturer and based on several intrinsic characteristics of the battery cells, manufacturability, mechanical strength, available space, needed energy capacity, and voltage level. The uniqueness of each battery pack, as well as the variety of used battery formats and chemistries, makes dismantling labour-intensive and recycling routes challenging to maintain material quality.

Chapter 3
The batteries that are currently fitted in electric vehicles are safe to use; however, with the increase of the demand for batteries, more sustainable batteries are needed. To reach that goal, different strategies are followed in parallel: research on novel materials (solid state, lithium sulphur, sodium ion, etc.) substituting scarce materials, integration of smart functionalities (sensors, self-healing) to increase the lifetime, accurate, on-board diagnosis tools (State of Health) for safety, digitalization of the battery production to increase the homogeneity of battery cells, and integration of the battery passport for transparent sharing of information. With the implementation of those research actions, batteries will have a longer life cycle, and become safer, as well as more sustainable.

Chapter 4
The carbon footprint and energy consumption of lithium batteries packs should be examined from a life cycle assessment approach, which considers the raw material acquisition, the production processes of the active materials, and the battery pack components, the distribution, and the end-of -life stage. The most significant contribution to the impact on climate change comes from manufacturing the battery cells; the energy used in manufacturing (especially electricity usage) and the production of the active materials of the cathode contribute the most to the emission of greenhouse gases. It is possible to reduce the carbon footprint of batteries by a factor of three when higher production volumes are considered and when an electricity mix with low carbon intensity is used during production.
Today, there are significant supply-chain (from material mining to battery manufacturing) risks linked to batteries needed in various industries in Europe. The battery materials with the largest supply risks are lithium, cobalt, natural graphite, and bauxite (for aluminium production) for current battery chemistries and niobium, silicon, and titanium for future generations of batteries. To improve European resilience, the European Commission is drafting a pathway to ramp up (1) the mining and refining of domestic raw materials, (2) domestic production of batteries, and (3) substitution and circularity of battery materials and components.

Chapter 5

Different end-of-life strategies emerge for lithium batteries, including repair, repurpose, and recycling techniques. When proper diagnostics and safe disassembly procedures are in place, repairing a battery pack is a good strategy to prolong the useful life of such battery. Predictive maintenance and self-healing properties are worthwhile to further develop and implement to prolong the useful life of a car battery. Third-party repair shops must be enabled to efficiently identify the exact component that needs to be replaced to repair a battery pack; fault codes generated by battery packs must be harmonized among OEMs and provided to repair shops.

When the diagnosis of a battery indicates that the State-of-Health is too low for a mobility application, several other options exist to recuperate parts of the value of the battery. Batteries that contain enough remaining capacity and potential lifetime can be repurposed in stationary applications to bring services to the transmission and distribution operators or to private customers. When a larger battery capacity is needed, the battery packs of electric vehicles are not dismantled but fully reused with their original casing, cooling system, and battery management system. When the battery needs to be dismantled, the labour cost increases together with additional costs for new components such as a new adapted casing, cooling circuit, and battery management system, limiting the potential economic feasibility of small second-life batteries. When reusing is not an option, the battery should follow a recycling process; typical recycling processes are direct, hydrometallurgical, and pyrometallurgical recycling, which have different material recovery rates and costs.

Chapter 6

Several standards and regulations are in place to prevent any possible failure in the usage stage of the battery. They are mostly related to abuse tests for Li ion battery based electric vehicles. In addition, in 2021, the Commission published a new EU Battery Regulation proposal, replacing the previous Battery Directive (2006/66/EC). The regulation has three main objectives: to a) strengthen sustainability, b) increase the resilience and close material loops, and c) reduce environmental impacts. To reach these objectives, the focus is on material recovery, recycling rates, performance and durability, and the integration of the battery passport among others.

Overall recommendations

To strengthen the circularity of automotive batteries, the following actions are recommended:

1) *Making propulsion batteries accessible for authorised repairers, increasing transparency of diagnostic information, and making batteries repairable*
2) *Strengthen the regulatory framework*
3) *Setting- up a battery passport with transparent data*
4) *Creating a reverse battery value-chain*
5) *Designing for circularity targets*
6) *Investing in training, education, and research*

2. Current Market perspective of batteries in electric vehicles

2.1. Description of current available electric vehicles and their batteries

The total passenger car fleet in the European Union (EU27) accounts 270 million passenger cars for a population of 447 million inhabitants. Fourteen million cars of the total fleet, or 5%, are labelled as vehicles driving with alternative fuels (BEV, HEV, H2, LPG, CNG, LNG), see Figure 1. All data on the alternative vehicle fleet of EU27 can be found on the web portal of the 'European Alternative Fuels Observatory' of the European Commission [1].

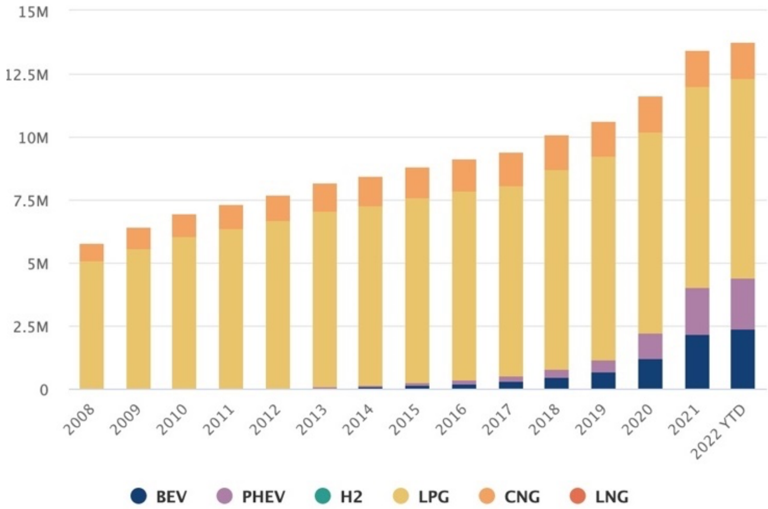

Figure 1: Total number of alternative fuelled (BEV, PHEV, H2, LPG, CNG, LNG) passenger cars (M1) [1]

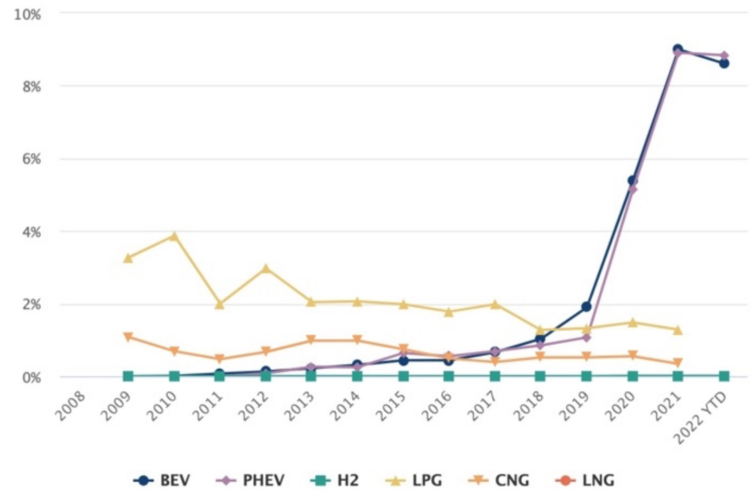

Figure 2: Newly registered alternative fuelled (BEV, PHEV, H2, LPG, CNG, LNG) passenger cars as a percentage of the total number of registrations [1]

However, this number is skewed towards older LPG cars (mainly in Italy (2,5 million) and Poland (3,5 million)), of which roughly 7,7 million are driving in Europe. Since 2018 a steep increase of BEV (Battery Electric Vehicle) and PHEV (Plugin Hybrid Electric Vehicle) in the total fleet is seen. By 2022 almost 4,5 million BEV (2,3 million) and PHEV (2 million) are driving in Europe. Figure 2 shows the newly registered alternative fuelled cars in Europe as a percentage of the total number of registrations. In 2021 BEV and PHEV represent each 9% of the market or 870.000 newly inscribed vehicles. It can be noted that the combined market share of BEV and PHEV is above 3% since 2019. In the market adoption of new type of products 3% is often seen as the point in

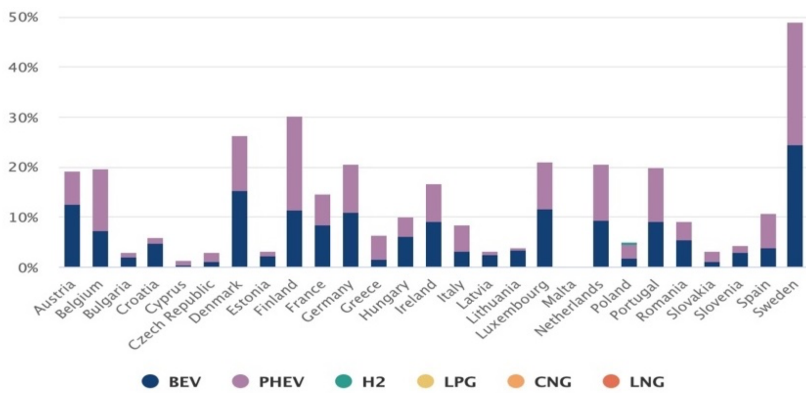

Figure 3: Newly registered alternative fuelled (BEV, PHEV, H2, LPG, CNG, LNG) passenger cars (M1) and vans (N1) as a percentage of the total number of registrations in 2021 [1]

which the new technology becomes more mainstream and changes in market share become exponential. The average market share of BEV and PHEV in EU27 in 2021 is almost 20% of all newly registered vehicles. The market share of LPG vehicles dropped to 1% LPG, the market share of CNG is 0,5%. Figure 3 shows a national resolution of the market share. The market share in Sweden is almost 50%, but many member countries have market shares beyond 10%. In Norway the BEV and PHEV group represented in 2021 85% of all newly registered cars. According to [2] the global demand for batteries had a volume of 180 GWh in 2018. It is expected that the demand will keep on growing with a yearly 25% to reach by 2030 a production capacity of 2,600 GWh. This is mainly due to the rise in sales of electric vehicles, which are expected to need yearly 2,300 GWh by 2030. China is expected to be the biggest market, accounting for 40% of the global market.

There is no standard battery in electric vehicles, the commonly used battery cells have different cathode compositions and types of formats. The main OEMs select together with their main battery suppliers the features and specifications best suited for their specific situation. There are three main types of cell formats that battery manufactures provide. There are smaller, mechanically strong **cylindrical cells**, that are heavier but easy to manufacture. Other battery providers manufacture **prismatic cells**, containing due to their design and size more capacity. On the other hand, there are **pouch cells** that don't have a strong hard case but have excellent energy density due to their lighter weight.

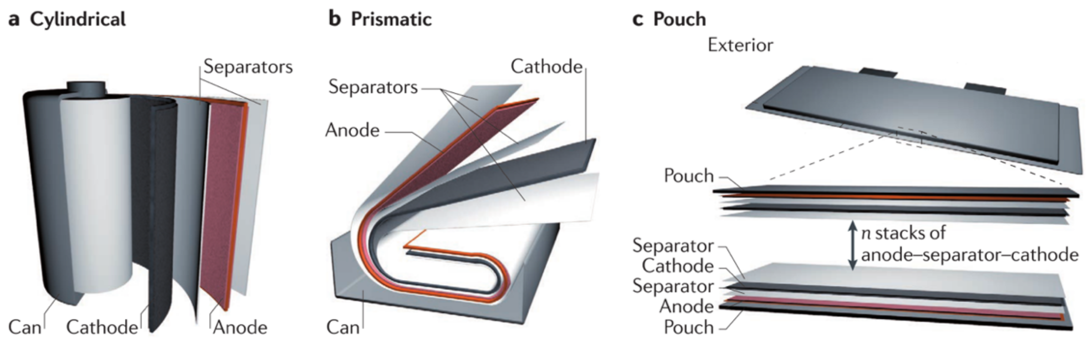

Figure 4: Li-ion batteries: a) Cylindrical cells, b) Prismatic cells and c) Pouch cells. [3]

Most car manufacturers are using prismatic or pouch cells today, however, no format really stands out among the others. It is a choice made by the manufacturer based on several intrinsic characteristics on chemistry and manufacturability. However, the choice of cell format influences the design of the eventual battery pack in the car, for example, the thermal management system and the mechanical strength of the casing of the modules and the pack. Three large battery

OEM	Cathode Type	Format	Some Key Suppliers
Ford	NMC	Pouch	LG Chem, SK innovation
Renault Nissan Mitsubishi	NMC	Pouch	Verkor, Envision AESC, LG Chem
BMW	NMC	Prismatic	CATL, northvolt, Samsung
VW	NMC, LFP	Prismatic	Samsung, northvolt, Gotion
Volvo	NMC	Pouch, Prismatic	LG Chem, northvolt
Daimler	NMC, LMFP	Pouch, Prismatic	CATL, LG Chem, Farasis, ACC
Jaguar	NCA	Cylindrical	Samsung
Hyundai	NMC	Pouch	LG Chem
Stellantis	LMFP, NMX	Prismatic	ACC, SVOLT
Tesla	LFP	Prismatic	CATL

Figure 5: Mapping of car manufactures and some of their battery suppliers, source [4]

producing conglomerates are based in South Korea, LG Chem, Samsung and SK Innovation. LG Chem produces cylindrical for Tesla, but in parallel diversified its options by producing pouch cells for other OEMs. Samsung focusses on the production of prismatic batteries to supply Volkswagen. SK Innovation manufactures pouch cells and supplies Ford, Mercedes-Benz, Volkswagen, Hyundai and Kia. CATL is the largest producer of lithium batteries and is headquartered in China. Both Gotion and CATL produce prismatic cells. The Japanese company Panasonic is the third largest battery producing company and supplies cylindrical cells to Tesla. Envision AESC is another Japanese company that supplies Nissan with pouch cells. In Europe there is Verkor and Northvolt [4].

There are different lithium battery chemistries available on market today that are commonly used by car manufacturers. Currently there are three widely used compositions for the cathode, namely LFP, NMC and NCA batteries.

Each chemistry has their own advantages and disadvantages making them attractive for specific vehicle applications. NCA batteries have commonly a higher energy density but are more expensive. LFP has a lower energy density, needing more volume inside the car. However, LFP chemistry provides better safety compared to NMC and NCA. LFP batteries are cheaper compared to batteries that need expensive cobalt in the cathode. NCA batteries on the other hand have the highest cycle life. NMC and NCA batteries are mostly used in current electric vehicles on the market because of their smaller volume and larger driving range. However, the cheaper and safer LFP batteries are seen as a good choice in larger vehicles, such a s buses and trucks, where volume is less of a limitation. Material scarcity and price pushes battery manufacturers to find methods to decrease active materials in the cathode or even substitute the critical materials. Table 1 provides an overview of battery chemistries and cell formats used by car manufacturers. The table lists the specific cell characteristics as well as the capacity and driving range of the full battery pack.

Table 1: Overview of key specification of lithium battery cells used in electric vehicles [5]

Cell format	Cell Chemistry		Cell Characteristics				Pack Characteristics		Vehicle		
	Anode	Cathode	Capacity (Ah)	Voltage (V)	Specific energy (Wh kg-1)	Energy density (Wh l-1)	Energy (kWh)	Driving range (km)	OEM	Model	Year
Prismatic											
Toshiba	LTO	NMC	20	2.30	89	200	20	130	Honda	Fit EV	2013
Samsung SDI	C	LMO-NMC	63	3.65	172	312	24	140	Fiat	500e	2013
Samsung SDI	C	LMO-NCA-NMC	60	3.70	122	228	22	130	BMW	i3	2014
Panasonic/Sanyo	C	NMC	25	3.70	130	215	24	190	VW	e-Golf	2015
Samsung SDI	C	LMO-NCA-NMC	37	3.70	185	357	36	300	VW	e-Golf	2016
Samsung SDI	C	LMO-NCA-NMC	94	3.70	189	357	33	183	BMW	i3	2017
Pouch											
AESC	C	LMO-NCA	33	3.75	155	309	24	135	Nissan	Leaf	2010
A123	C	LFP	20	3.30	131	247	21	130	Chevrolet	Spark EV	2012
LG Chem	C	LMO-NMC	16	3.70	-	-	35.5	160	Ford	Focus EV	2012
LG Chem	C	LMO-NMC	36	3.75	157	275	26	150	Renault	Zoe	2012
Li-Tec	C	NMC	52	3.65	152	316	17	145	Smart	ForTwo EV	2013
SK Innovation	C	NMC	38	3.70	-	-	27	145	Kia	Soul EV	2014
AESC	C	LMO-NCA	40	3.75	167	375	30	172	Nissan	Leaf	2015
LG Chem	C	NMC	56	3.65	186	393	60	383	Chevrolet	Bolt	2016
LG Chem	C	NMC	59	3.70	241	466	41	400	Renault	Zoe	2017
LG Chem	C	NMC	60	3.50	-	-	71-95a	300-448a	Audi	e-Tron	2019
Cylindrical											
Panasonic	C	NCA	3.2	3.60	236	673	60-100a	330-500a	Tesla	S	2012
Panasonic	Si/SiO-C	NCA	3.4	3.60	236	673	60-100a	330-500a	Tesla	X	2015
Panasonic	Si/SiO-C	NCA	4.75	3.60	260	683	75-100a	490-630a	Tesla	3	2017

Figure 6 shows the capacities and driving ranges of the vehicles as reported by the car manufactures. The data is available on the website of the European Alternative Fuel Observatory [1]. It contains vehicles from many manufacturers of electric vehicles that are available in 2022 (Aiways, Audi, BMW, Citroen, Cupra, Dacia, Fiat, Ford, Genesis, Honda, Hyundai, JAC, Jaguar, Kia, Lexus, Mazda, Mercedes, MG, Mini, Nissan, Opel, Peugeot, Polestar, Porsche, Renault, Seres, Skoda, Smart, SsangYong, Tesla, Toyota, Volkswagen and Volvo). The battery sizes range from 30kWh to 105kWh with a driving range of 170km to 505 km respectively. The capacity of batteries is increasing throughout the years as customers demand larger driving ranges and battery production cost are decreasing rapidly. Many electric vehicles on the market have a battery capacity exceeding 60kWh and a driving range more than 300km. If the average electricity consumption is 20kWh/100km and the average kilometres travelled per day is 50km it is clear that there is a lot of unused battery capacity inside parked, grid-connected electric vehicles. Customers of electric vehicles need as well publicly accessible charging infrastructure.

Figure 7 show the number of charging spots that are currently deployed in the different member states. A division is made on the power rating of the charger. Fast chargers exclusively use DC (direct current). With growing battery capacity, the power rating of the chargers is increasing as well, limiting the charging time. The massive roll-out of slow or medium recharging points indicates the strategy to charge the vehicle for longer period upon arrival at destination. Fast recharging points on the other hand have a comparable strategy to a conventional highway tank station, it increases the length of a single trip.

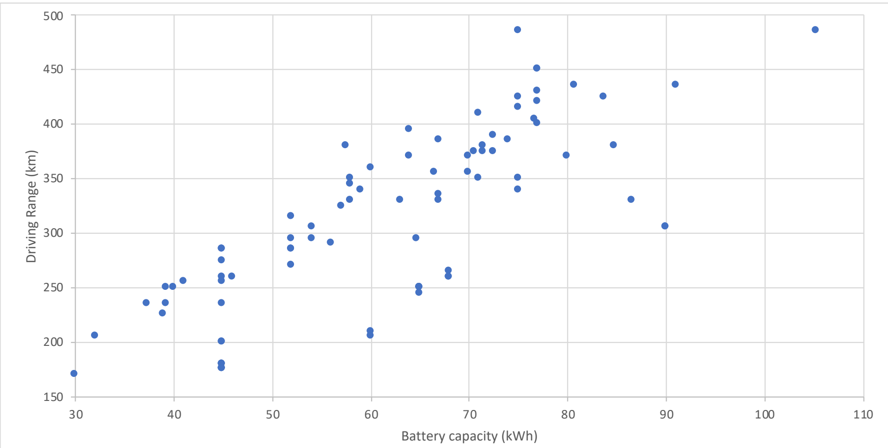

Figure 6: Mapping of driving range and battery capacity of electric vehicles on market, data from [1]

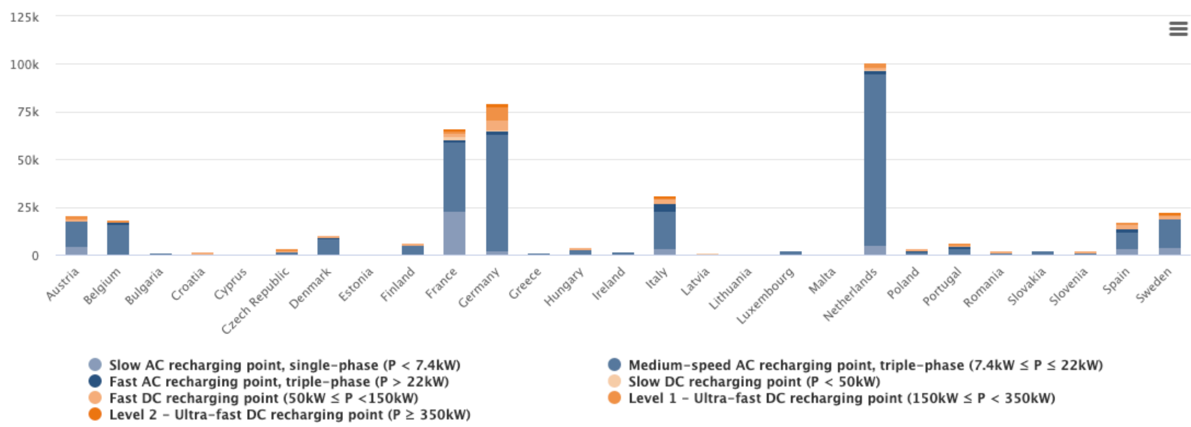

Figure 7: Total number of AC and DC charging spots, divided in slow, medium and fast charging power [1]

2.2. Battery pack components and composition

Figure 8 presents the basic components of a battery pack. Every battery cell contains two electrodes, being the cathode and the anode and a separator and electrolyte. These essential elements are needed to allow electric energy to be stored by lithium electrons. The active materials in the cathode are often scarce and precious (nickel, cobalt and manganese). The anode is made up out of graphite, carbon and silicon. The function of the separator is to separate the anode from the cathode and the electrolyte allows the electric current, in the form of lithium electrons, to flow between the two electrodes. The battery module contains several battery cells that are connected to raise voltage levels. Most often modules have their own packaging and control unit. Several modules are connected in series or parallel to form a battery pack. The battery pack also contains a strong casing and a battery management system with onboard diagnostics and cooling system.

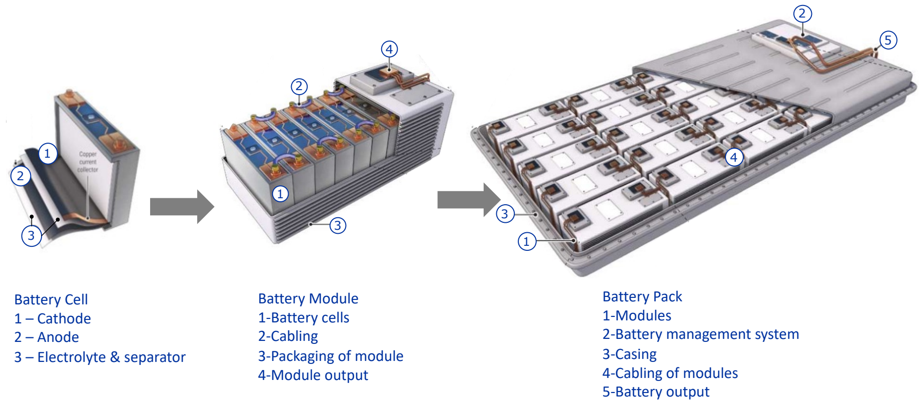

Figure 8: Basic composition of a battery pack and modular build-up, graphic adapted [6]

Figure 9 gives three examples of battery packs in electric vehicles (Tesla model S, BMWi3 and Nissan Leaf). The three designs examined are from model year 2014 and based on vehicle teardown information [7]. The figure shows three older vehicles making them more likely to be found today in an end-of-life situation. The three battery packs are fundamentally different from each other in terms of cell size, format type (respectively cylindrical, prismatic and pouch cells), chemistry (respectively NCA, NMC and LMO) and battery pack voltage levels, weight and capacity. The Tesla cylindrical cells are produced by Panasonic, the BMW prismatic cells are produced by Samsung SDI and the Nissan pouch cells are produced by AESC (Automotive Energy Supply Corporation).

Figure 10 shows the full dismantling of the battery pack of a BMW i3 in four levels, its integration in the vehicles, the components of the battery pack, the modules and eventually the individual cells.
The battery pack has a nominal voltage of 325V, a weight of 284 kg and a dimension of 1666 x 993 x 173 mm. Interestingly, without changing the main characteristics of the battery, there is a significant evolution in the battery capacity through the years. With the same volume and weight, the 2014 model was packing a battery with a total of 22kWh. The capacity of the battery pack increased with the 2017 model to 33kWh and with the model of 2018 to 42kWh. This doubling of battery capacity without changing the volume was possible due to developments of Samsung. In 2014 the individual battery cells contained 60Ah, while the newer generation in 2018 contained already 120Ah.

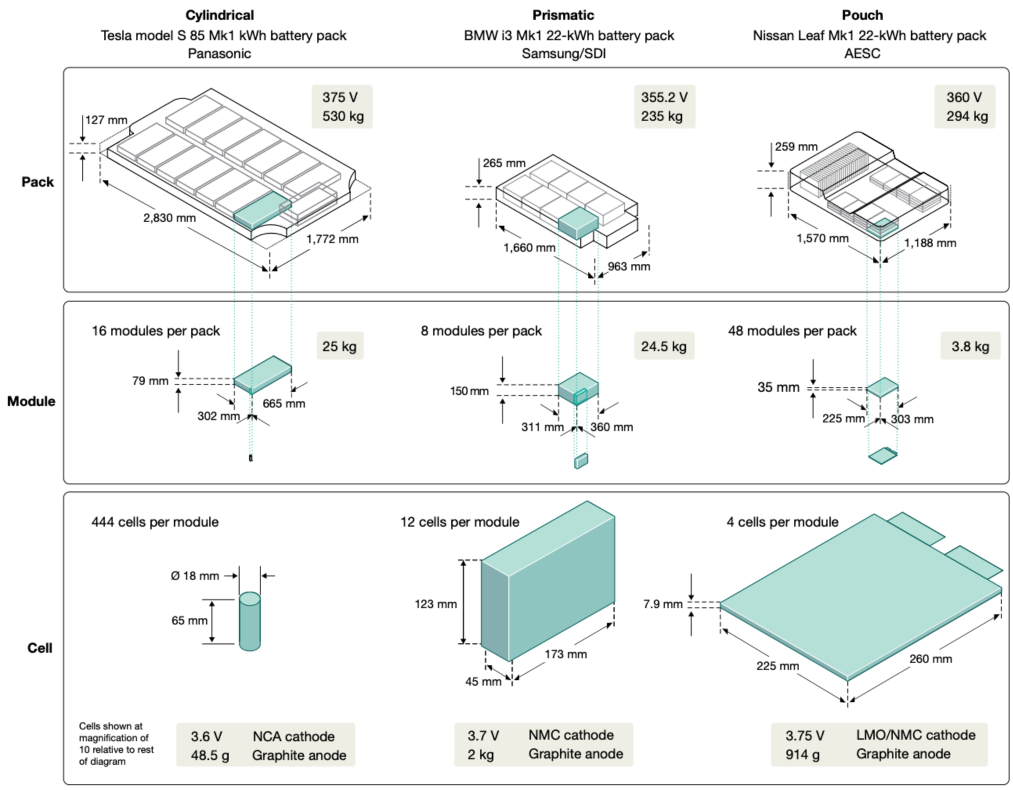

Figure 9: Different physical configurations of battery packs in three electric vehicles [7]

Car Integration:

The first part of the figure shows the integration of the battery pack in the vehicle and the location of the electric motor. The metallic casing of the battery pack is bolted to the chassis of the car. The orange connector connects to the power and the data of the battery pack.

Battery pack:

Removing the lid shows the main components of the battery pack. It consists out of 8 modules that each have a controller that connects to the Battery Management System. The cooling system is made-up out of a compressor and a cooling circuit which is running under the modules in this configuration. Next to the orange power and data connection a vent is cutting through the casing of the battery pack. The vent enables potential gasses (gasification of the electrolyte) to leave the battery pack in a secure way during a calamity.

Battery Module:

The battery module consists out of 12 battery cells that are connected to reach the desired output power. Each cell is measured continuously via the electric and power control system.

Battery cell:

The battery cells have a negative and a positive terminal, a seal pin that is used to electrolyte inside the battery during production, a vent to release gasses and electronics to ensure overcharging is not possible on cell level. The picture shows a Samsung SDI94 lithium-ion battery cell with NMC chemistry. The cell has a weight of 2 kg and a volume of 173x125x45mm. The nominal voltage is 3,68V, the nominal capacity is 92 Ah and an energy capacity of 0,345 kWh.

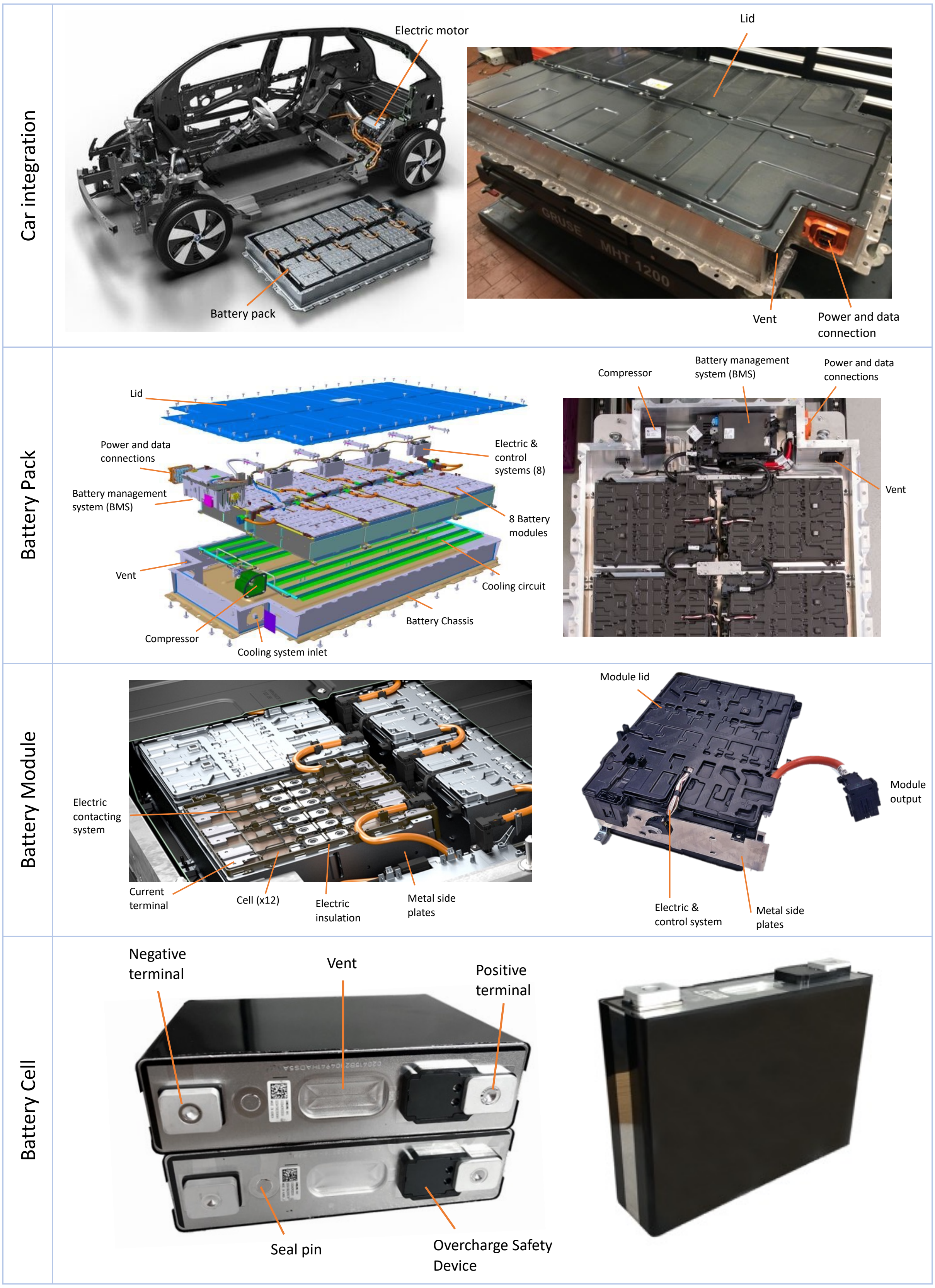

Figure 10: Disassembly of the battery pack of a BMWi3 electric vehicle, graphic adapted from various internet sources

3. Battery technology

3.1. Existing Battery Technologies

3.1.1. Technology Overview

Li Ion battery technology is the preferred technology for mobility applications. Although all Li Ion batteries use lithium ions as the charge carriers between the anode and the cathode, there are different types of batteries depending on the used materials. The majority of the Li Ion batteries use the use graphite as the anode; therefore, the main significant change is the cathode material. The different Li Ion technologies are presented and compared in terms of specific energy, specific power, calendar life, cycle life, safety, stability and cost. Since their characteristics are different, the field of application of them also varies, from consumer electronics to heavy duty or grid applications. The presented technology is already a mature battery technology which can be found in many applications, such as, Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminium Oxide (NCA), Lithium Manganese Oxide (LMO), Lithium Cobalt Oxide (LCO), Lithium Titanite (LTO), Lithium Nickel Manganese Cobalt Oxide (NMC) as well as the High Energy NMC. Additionally, High Voltage Spinel (TRL6-7) and Solid state (TRL4-5) are being studied and developed in order to enhance the performance characteristics of the current technology.

- The *specific energy* feres to how much energy a battery can hold per unit volume Wh/l (volumetric energy density) or per unit weight Wh/kg (gravimetric energy density). Both units (volumetric and gravimetric) are important factors to be considered in applications like mobility where volume and weight are of great importance.
- The *specific power* is quantified by W/l (volumetric power density) or W/kg (gravimetric power density). This parameter is of high importance for applications where high power is needed such as power tools and heavy-duty vehicles.
- *Calendar life* refers to the amount of time the battery can maintain its health (expressed by its capacity) over time.
- *Cycle life* refers to the ability of the battery to maintain its health (expressed by its capacity) during performed charge and discharge cycles.
- *Safety* refers to the limitations that the technology has in voltage, current and temperature. This 3-parameter limitation is defined as Safe-Operating-Area where the batteries should always be inside. The crossing of the limitations of any of the parameters, such as over-voltage, may lead to the activation of hazards like thermal runaway.
- *Cost* presents an estimation considering the specific technology together with the needed battery management system control and the market situation.

In Table 2, a comparison of the different technologies and their main applications is showed. As can be seen, meanwhile LCO is a technology valid for consumer electronics, NMC and LPF technology is suitable for any kind of application. However, NMC has a higher energy density making NMC a better candidate for mobility applications although the cost will be higher.

Chemistries with a better score on power can be (dis)charged at higher power ratings than others, which could result in shorter charging period when the power rating of the recharging points allow fast charging.

Table 2: Comparisons of different types of Li-Ion batteries[8].

Type	Chemistry	Performance						Main Applications						
		Energy	Power	Calendar Life	Cycle Life	Safety/Stability	Cost	Consumer Electronics	Power Tools	Light Duty Vehicles	Cars	Trucks/ Commercial Vehicles	Buses	Grid
LFP (Lithium Iron Phosphate)	$LiFePO_4$	++	++	++	++	+++	+	•	•	•	•	•	•	•
NCA (Lithium Nickel Cobalt Aluminium Oxide)	$LiNiCoAlO_2$	+++	+++	++	++	+	+	•		•	•			•
LMO (Lithium Manganese Oxide)	$LiMn_2O_4$	+	+++	-	++	++	++	•	•	•	•			•
LCO (Lithium Cobalt Oxide)	$LiCoO_2$	++	++	+	+	+	+	•						
LTO (Lithium Titanate Oxide)	$Li_4Ti_5O_{12}$	-	+++	+	+++	+++	-				•		•	•
NMC (Lithium Nickel Manganese Cobalt Oxide)	$LiNi_xCo_xMn_xO_2$	+++	++	++	++	++	++	•	•	•	•	•	•	•
HE-NMC (High Energy Lithium Nickel Manganese Cobalt Oxide)	$LiNi_xCo_xMn_xO_2$	++++	++	+	+	-	++	•	•	•	•	•	•	•
HVS (High Voltage Spinel)*	$LiMn_{1.5}Ni_{0.5}O_4$	++++	++	+	+	-	+	•	•	•	•	•	•	•
Solid State**		++++	++	++	-	+++	++	•	•	•	•	•	•	•

* currently at TRL6-7
** currently at TRL4-5

3.1.2. Battery Management System

The Battery Management System (BMS) is the control device that makes sure the battery is inside the Safe-Operating-Area. Additionally, the BMS runs several algorithms to keep the battery safe along its useful life. The BMS has different main functionalities, such as: 1) Monitoring, 2) Diagnosis 3) Balancing 4) Thermal Management 5) Safety 6) Communications.

- Monitoring

Monitoring is done through the Data Acquisition System (DAQ) of the BMS. This is the most critical feature of the system since all algorithms and decisions will be taken based on this data being voltage, current and temperature. The analogue signals are brought into the DAQ unit where the signals are transferred from analogue to digital. Afterwards, the processed and stored in the memory to be used/communicated in a later stage. DAQs can be integrated as part of the BMS board or installed on the cells. In the first case, the cables from all sensors need to be connected to the BMS, in the second case on the contrary the DAQ sends the date to the BMS through a communication bus [9].

- Diagnosis

There are various state estimations that can be estimated from a battery. The most common ones are the state of charge (SoC) and the state of health (SoH). The SoC is defined as the fraction of the available capacity stored in a battery in relation to its capacity and energy [10].

In other words, the SoC indicates the amount of charge that is left in the battery. The SoC is calculated in %, 100% means the battery is full, 0% means the battery is empty. One could think that measuring the cell voltage to deduce its remaining charge can be a possibility, however, SoC vs Voltage curves vary depending on the current, temperature and degradation.

Moreover, some Li Ion technologies suffer from hysteresis effect between charging and discharging curves. Furthermore, those effects occur per cell while each cell behaves differently and have different aging and performance effects, making the SoC estimation of a full pack more challenging. The most used method to estimate the SoC are Coulomb Counting [11] (medium accuracy however low lost and low computational effort), Open Circuit Voltage (lowest accuracy) and Extended Kalman filter [12] (used for high accuracy, higher computational effort). The selection of the method relies on the need of the application and its usage. It is important to highlight as well that the SoC doesn't refer to the full battery capacity but the usable battery capacity. To avoid critical failures or risks that may come from overcharging and over discharging the battery cells do not use their full capacity 0-100%. In addition, a capacity % is also reserved for possible BMS usage in critical situations so the management can act properly by for example activation of the cooling system. Therefore, the full capacity of the battery differs from the usable capacity, being a lower capacity %.

The SoH reflects the ability of a battery to store energy and provide a certain power relative to its initial or ideal conditions. Following the UNECE battery GTR No 22, SoH refers to the health of the battery at a given point in its life, this term is not commonly defined and is determined through a variety of different technologies [13]. A SoH lower than 80% means that the battery should be replaced from a mobility application [14]. Similarly, to SoC, SoH estimation is not a straightforward calculation. There are several methods to estimate it, based on experimental methods (such as EIS, HPPC) and adaptive models (such as Kalman Filter, Neural Networks, etc.). In this case as well, a trade-off between accuracy and computational effort must be made which will depend on the requirements of the final application.

However, there are more states that can be processed by the BMS such as, state of energy (SoE), state of power (SoP), state of safety (SoS). SoE refers to the degradation of the battery capacity over lifetime, a SoE lower than 80 % is considered End of Live. SoP is related to the resistance growth and the capability of the battery to provide a certain power. A SoP lower than 50 % is considered as End-of-Life stage. SoS is inversely proportional to the abuse on the system, i.e., the more the limits of state of the art are reached, the more the system is abused, the more SoS decreases [15,16]. In addition, following the UNECE battery GTR No 22, two new related metrics were defined, the State of Certified Energy (SOCE) and the State of Certified Range (SOCR). Both metrics represent a percentage of the certified battery energy or electric range remaining at a given point in time. In the case of SOCE, it was decided to base the matric on the Usable Battery Energy (UBE) [17].

- Balancing

Voltage balancing of cells or modules is of utmost importance, as it prevents overcharge and overdischarge failures of individual cells, caused by irregularities after a large number of charge and discharge cycles [18]. Therefore, the aim of cell balancing within the BMS is to avoid and control that the cells will not over pass any overcharge or over discharge limit. This problem may occur drastic problematic in the battery pack if not controlled with irreversible damage. Since the cells are not at the same voltage level, the safety limit will be reached by the cells or modules with the lowest SoC or voltage forcing the BMS to stop the discharge operation. Following the same rationally, the upper safe voltage limit will be reached by cells or modules with higher SoC or voltage forcing the BMS to stop the charge [19]. These imbalances lead to deterioration of the system performance and energy loss of the total storage unit. There are two type of balancing techniques, passive and active [20].

In passive methods, the excessive energy of the cells/modules with higher voltages is dissipated until they reach the same voltage of the lower voltage cells/modules. This method is simple however the residual energy is lost [21]. In active balancing methods, the excessive energy us passed from higher voltage cells to lower voltage cells. In this case, power electronics and actives components are needed [22]. The transfer of energy can be in cell to cell, cell to pack, pack to cell and even cell to load. Current research balancing techniques are more sophisticated since they can detect failure cells and bridge them to avoid possible risks that will impact the full pack. However, these novel techniques take a higher computational effort, making them less easy to implement in the BMS.

- Thermal Management

The Battery Thermal Management System (BTMS) is part of the BMS. Via the DAQ the temperature is monitored and when needed the BTMS will take action to activate the cooling or heating control to ensure an optimal battery temperature. For activation, the cooling or heating system valves, coolant flow, etc will start. Furthermore, if the temperature exceeds a critical value, the BTMS will communicate with the safety system to proceed with further actions [23]. When those limits are exceeded the BTMS will activate the cooling system. There are different possibilities of cooling systems, passive, active and hybrid. On one hand, active cooling systems are based on liquid and forced air cooling through an external energy source. On the other hand, passive battery cooling systems such as phase change material (PCM) and heat pipe do not use any external energy source. The third possibility is a combination of both systems named hybrid cooling system. Depending on the used battery chemistry and the application, the thermal management and the cooling system will be different and therefore they need to be tailor made. Although the focus is to cool down the battery, a heating system can also be implemented and controlled by the BTMS. These systems are used in cases such as colder countries in which the battery needs to be warmed up before usage.

- Safety

In case of fault, Li Ion batteries are hazardous as they are flammable, and they could explode or release toxic gases [24]. Therefore, for an EV application the safety requirements to be followed are critical and a BMS compatible with ISO 26262 standard on functional safety on functional safety shall be in place [25]. The BMS is in constant communication with the protection devices in case the safety protocol is activated. The safety protocol follows two categories, fault detection and fault mitigation. Most of the commercially available BMS can cover a simple fault detection protocol, where overcharge, over discharge and over temperature is detected [26]. These faults can be easily detected by comparison of a reference value and a sensor output [27].

However, other more complicated faults may happen such as sensor faults, initial contact, cell internal short circuits, etc. [28]. Mitigation actions are activated once a fault in a cell, module or pack is detected. Depending on the configuration of the Battery Energy Storage

System (BESS) and the location and type of the fault, the mitigation action may differ. In the worst-case scenario, the disconnection of the BESS may occur, however other alternatives such as bypassing the faulty cell/module using switches can take place [29]. When bypassing the faulty cell/module balancing can also get activated to share the power with other cells [30]. Moreover, anytime the BESS does not provide its nominal performance, maintenance shall take place.

- Communications

In a large-scale BESS system, a high number of cells can be implemented, in those cases the structure of the BMS can follow a master-slave hierarchy, being the modules the slaves and the entire pack the master BMS. In any hierarchy approach the communication shall be secure and reliable for a correct performance of the battery. Controller Area Network (CAN) type is widely used for batteries for real-time distributed control, more concretely due to its high communication baud rate and high reliability [31]

3.1.3. Diagnosis

- Degradation Mechanisms

It is challenging to classify and separate individually the degradation mechanism phenomena that could occur in a Li Ion cell due to its complexity and simultaneous occurrence (Figure 11). The battery scientific community have agreed on categorizing the degradation mechanisms in three main modes: Loss of Lithium Inventory (LLI), Loss of active Material (LAM) and Ohmic Resistance Increase (ORI) [32].

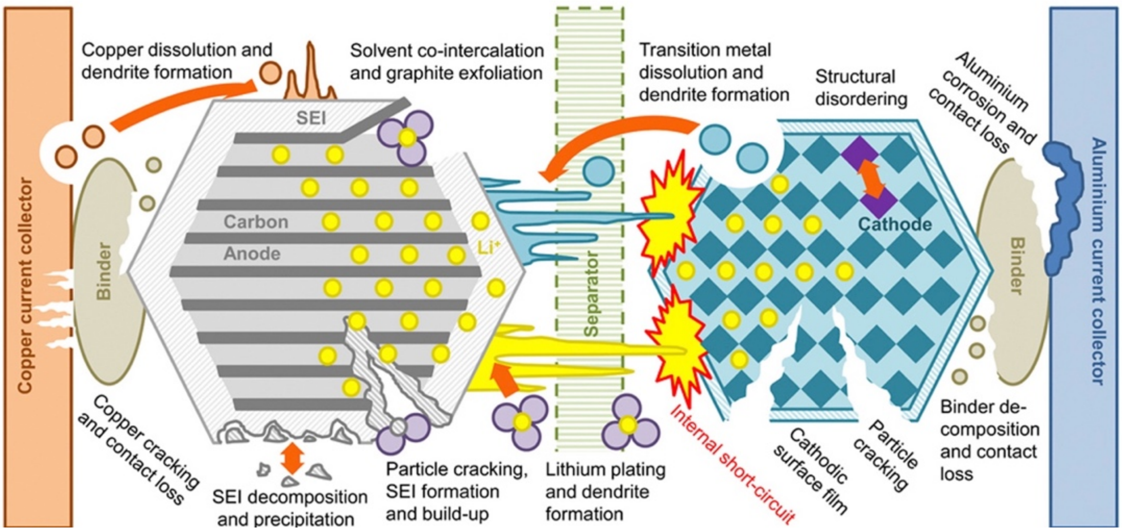

Figure 11: Common degradation mechanisms in Li-ion cells [32]

LLI refers to the degradation mechanisms that consume the available lithium ions due to parasitic side reactions. Consequently, the amount of available charge carriers is reduced. Cycling between the anode and cathode will be then produced with less amount of lithium ions which leads to capacity fade. Lithium plating, decomposition of the electrolyte and surface film formation are the main responsible actors causing LLI. Furthermore, the formation and growth of surface films also affects to power fade.

LAM refers to the degradation mechanisms that detach parts of the active materials from the (de-)lithiation reaction. This phenomenon can occur at both, the anode and cathode. The mechanisms producing LAM depend on the lithiation level and the affected electrode. However, the most common ones are graphite exfoliation, structural changes in the electrode, particle cracking and electronic and ionic active material isolation. Any of these phenomena causing LAM can lead to capacity fade but also power fade.

LLI and LAM are caused mainly due to the thermodynamic variations, however ORI is affected by the cell kinetic behaviour. ORI is the responsible of higher losses because of the increased polarization of the cell. Reduced ionic conduction of the active material, hindrance of charge transfer reactions at the electrode surface, electrode contact loss and increased ionic resistivity of the electrolyte are some of the factors which create ORI. Moreover, ORI also contributes to the decrease of the available capacity since the lower/upper cut-off voltage will be reached more rapidly during discharge/charge due to higher polarization [33].

- Degradation Stressors

Batteries age while being used and while not used. The deterioration while operando through the repetitive action of charging and discharging is called cycle aging. Calendar aging refers to the deterioration of the battery while not being used. Acknowledging and understanding both types of degradation helps in understanding battery ageing and it is essential to develop accurate SoH estimation algorithms. The most common degradation mechanisms, their respective cause, degradation mode, and resulting effect are summarized in Figure 12 [32].

SEI growth, electrolyte decomposition and LAM resulting from transition metal dissolution [34] have been identified to be the main degradation mechanisms affecting to the calendar ageing. Those degradation mechanisms are caused by mainly the storage temperature, storage SoC and length of storing (time). A more severe degradation was found in cells which were stored at high temperatures and high SoC. High temperatures accelerated the parasitic side reactions while high SoC may cause lithiated graphite [35]. As a conclusion, batteries shall be stores at mid SoC and room temperature (25 degrees). Considering cycle ageing, the main stressors are temperature (optimal temperature is for Li-ion batteries is 25–40 °C), current rate, and depth of Discharge (DoD) [36].

Similar effects as already described for calendar ageing, such as accelerated SEI formation, electrolyte decomposition and possible transition metal dissolution may happen while cycling at elevated temperatures. Cycling at lower temperatures on the contrary will slow down the Li+ ion diffusion causing lithium platting [37].

Cycling the batteries at high current and/or high DoDs have generally similar negative effects since over- and under- charged regions at the electrodes can be reached. Decomposition of the electrolyte and lithium plating may happen caused by the overpotentials [38]. Independently at each of the electrodes, structural disordering, active material decomposition and transition metal dissolution may happen due to an over-delithiated cathode while current collector dissolution may happen due to an over-delithiated anode [39].

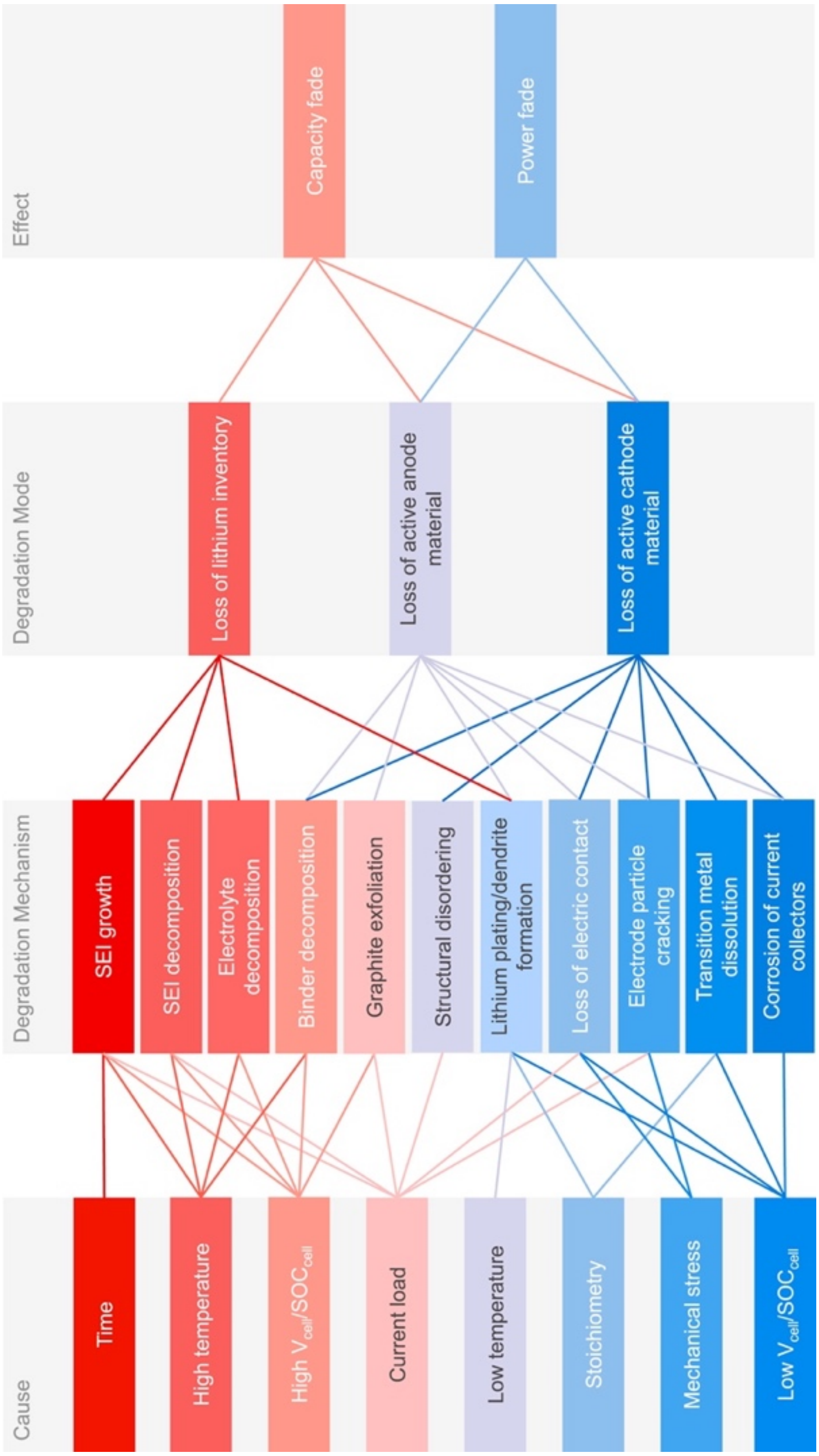

Figure 12: Graphical summary of interplays between degradation stres- sors, mechanisms and their respective classification mode. Reproduced from [32]

- State of Health

Several causes affect to the degradation of the battery resulting in power fade and capacity loss impacting the performance of the battery. The track and accurate estimation of the SoH is therefore crucial to ensure the safe and reliable operation of the batteries. As previously defined, the SoH reflects the battery performance relative to its pristine condition.

The SoH can be specified in reflecting energy (capacity loss over time, SoH_{energy}) or power capability (increase of the resistance over time, SoH_{power}). This selection is mostly driven depending on the application which usually falls as energy oriented to BEV and power focused to HEVs. In this regard the End of Life (EoL) limits are also different for both categories. EoL is reached at SoH_{energy} at 80% referring to the capacity decrease and for SoH_{power} at 200% referring to the resistance increase [40].

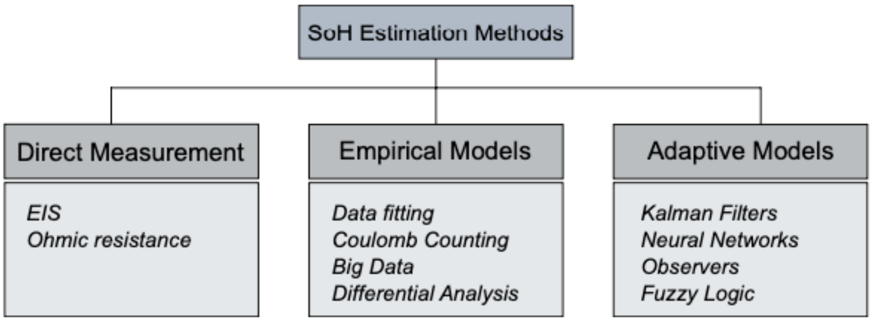

Figure 13: Classification of non-exhaustive SoH estimation methods in literature.

As previously said, SoH is not directly measured, on the contrary, it needs to be estimated. Additionally, a wide variety of factors, sometimes acting independently sometimes acting simultaneously, cause battery degradation. Several SoH estimation methods have been developed which can be categorized depending on the type of method, direct measurements, empirical models and adaptive methods. Direct measurements such as EIS and Ohmic resistance measurements are obvious candidates due to the internal growth of the battery over time due to usage and degradation [41]. While both methods are widely used to characterize empirical models and algorithms due to their simplicity, they are not practical for online applications [42]. Other alternative methods are in place such as empirical models (data fitting, coulomb counting, differential analysis, etc.) and adaptive models (Kalman filters, neural networks, observes, etc.) [43]. In this case, a trade-off between accuracy and computational effort will take place depending on the final application and characteristics of the microcontroller specifications.

3.2. Emerging Battery Technologies

3.2.1. Smart functionalities

Battery degradation is unavoidable. There are many factors affecting to the battery life degradation, which is more and more deeply understood by the scientific community. Therefore, alternative like self-healing or sensor integration comes in place to use safer and longer lifetime batteries. Non-invasive sensors are now under research and development to track the chemical and electrochemical reactions of batteries. In addition, self-healing properties to stop and heal the main degradation of batteries are as well under study. A combination of both will lead to the development of sustainable, safer, longer lifetime and affordable batteries [44].

- Sensor Integration

Regarding sensor development, three pioneering European projects are now in the development, testing and validation of novel sensors to be applied in the battery field: Spartacus [45], Instabat [46] and Sensibat [47] The three projects aim to develop and validate affordable sensors capable of detecting the different degradation mechanisms that happen in a battery cell. Several sensors will be studied in parallel on the ongoing EU projects.
Spartacus focuses on developing mechanical, acoustic, electrochemical impedance and temperature sensors. Sensibat will measure in real time the internal cell temperature, pressure, conductivity, and impedance. Instabat aims to embed four physical sensors (optical fibers with Fiber Bragg Grating and luminescence probes, reference electrode and photo-acoustic gas sensor), and develop two virtual sensors (based on electro-chemical and thermal reduced models). All projects will develop advanced battery management systems by implementing the smart SoX estimations which are enhanced by using the inputs of the different sensors. Finally, the sensorized cells will be tested and validated at module level together with the integration of the needed advanced BMS.
These innovative solutions will improve the understanding of degradation of the battery technology by closely tracking the evolution of these parameters with the physicochemical degradation phenomena taking place at the battery cell's core and will therefore improve the battery's functional performance and safety.

Although the implementation of sensors in a battery is a novel concept, certain goals are aimed to achieve in the short (+2 years), medium (+5 years) and long term (+10 years). In short term, understanding which sensors are successful to be integrated in a battery cell and providing battery insights (e.g., interface dynamics, electrolyte degradation, dendritic growth, metals dissolution, and materials structure change). In the medium term, the integration of the different sensors and connection to the BMS is expected. Additionally, understanding on the manufacturing and recycling challenges as well as the economic constrains are expected to be understood. In the longer term, masterization of sensorization on batteries, and communication with BMS is expected together with the advanced solution of combining self-healing and sensors together for lifetime extension.

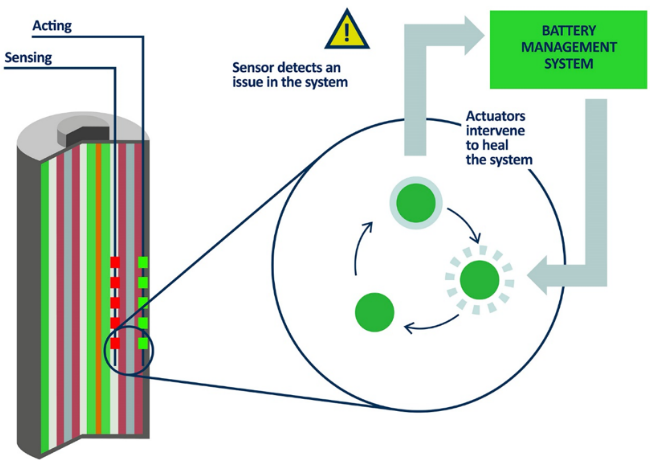

Figure 14: Smart Functionalities: Sensing [43]

- Self- Healing properties

Degradation mechanisms can be categorized depending in their type of degradation. Mechanical degradation or chemical/electrochemical degradation. On one hand, particle cracking and loss of electrical connectivity are considered mechanical degradation. On the other hand, solid electrolyte interface growth and decomposition, dissolution of transition metals, gas evolution, dendrite formation and current collector corrosion are categorized as chemical/electrochemical degradation. Each type of degradation will be suited to different self-healing processes, additionally, this also may differ depending on the technology that is being treated. Bat4ever [48] and HIDDEN [49] are two European projects that are focused on testing and validating self-healing properties in batteries.

BAT4EVER deals with self-repairing processes which will compensate volume changes caused by the usage of Silicon. Silicon is an abundant and cheap material. It has a great potential to be used in batteries due to its high specific capacity (ca. 4200 mAh/g) with 0.4 V operating voltage against Li metal [50]. However, silicon can change its volume up to 300% when lithiation. This makes the material unable to preserve their capacity when longer cycling. In this case, the development of a dedicated self-healing method will enable long-term cycle life on higher capacity battery cells. For that, BAT4EVER focuses on developing (i) Self-healing functionalities through polymer binder surface coating to protect electrodes (ii) Utilization of Silicon anodes, (iii) Oxidation and thermal stable core/shell structured NMC cathodes, (iv) novel electrolytes based on polymerized ionic liquids. HIDDEN aims to develop and implement a self-healing thermotropic ionic liquid crystal electrolyte, a piezoelectric separator and protecting additives. The electrolyte is aiming to break the formed dendrites and the separator aims to dismiss the dendrite formation itself. Both projects aim at upscaling the battery material and cell technology that has been developed and tested and validated at higher scales. In addition, multiscale modelling will be as well developed in both projects. The development of novel self-healing batteries will bring the possibility of using longer lifetime and more sustainable batteries while gaining deep knowledge on the degradation and the self-healing properties that can be successfully implemented. Furthermore, following the European work programme, now both concepts self-healing and sensors are brought up together with a triggering effect.

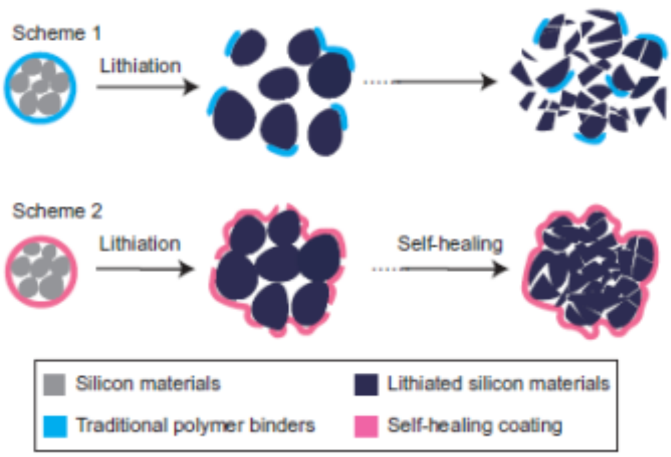

Figure 15: Smart Functionalities: Self-Healing [43]

In the same way as in sensors, in short term the understanding and feasibility of self-healing properties is aimed to be achieved. In medium term, the triggering of those self-healing properties with external stimulus is aimed to be achieved. At longer term, the goal is to link and successfully develop a self-healing triggered effect through activation of the input of the sensors. In addition, communication with the BMS should also be masterized at long term.

3.2.2. Novel Technologies

The batteries on the road are safe and cover the technical needs from the user perspective, batteries can still technically and sustainably improved. On one hand, avoiding critical materials is one of the targets of the EU, therefore other novel technologies such as Sodium Ion and Lithium Sulphur are under research. On the other hand, other technological bottlenecks such as increasing the energy density and overcoming fast charging is still under research. To achieve higher energy densities a promising technology is solid state batteries, however the readiness level of this novel technology is not ready for the market.

Additionally, many efforts are being done to improve the battery technology by including sensors and self-healing properties for longer and safer batteries, material research to reach higher energy and power densities is always ongoing. Material research is key to lower the cost of batteries since 70% of the battery cost concentrates in the materials (cathode, anode, electrolyte, and separator). There are several mature Li ion battery technologies which are suitable for many applications as already seen in a previous section. However, as can be seen in Table 3 research on Li Ion batteries is growing further than Generation 1 and 2. Many efforts are now dedicated to improving Generation 3 which deals with the optimization of Li Ion batteries, Generation 4 which focuses on Solid state technology and Generation 5 dealing with other battery technologies as well as lithium-air.

Table 3: Future battery technology generation categorization [a]

Battery Generation	Electrodes active materials	Cell Chemistry / Type	Forecast market deployment
Gen 1	• Cathode: LFP, NCA • Anode: 100% carbon	Li-ion Cell	current
Gen 2a	• Cathode: NMC111 • Anode: 100% carbon	Li-ion Cell	current
Gen 2b	• Cathode: NMC523 to NMC 622 • Anode: 100% carbon	Li-ion Cell	current
Gen 3a	• Cathode: NMC622 to NMC 811 • Anode: carbon (graphite) + silicon content (5-10%)	Optimised Li-ion	2020
Gen 3b	• Cathode: HE-NMC, HVS (high-voltage spinel) • Anode: silicon/carbon	Optimised Li-ion	2025
Gen 4a	• Cathode NMC • Anode Si/C • Solid electrolyte	Solid state Li-ion	2025
Gen 4b	• Cathode NMC • Anode: lithium metal • Solid electrolyte	Solid state Li metal	>2025
Gen 4c	• Cathode: HE-NMC, HVS (high-voltage spinel) • Anode: lithium metal • Solid electrolyte	Advanced solid state	2030
Gen 5	• Li|O_2 – lithium air / metal air • Conversion materials (primarily Li|S) • new ion-based systems (Na, Mg or Al)	New cell gen: metal-air/ conversion chemistries / new ion-based insertion chemistries	>2030

One of the targets in developing sustainable batteries is to reduce the used Cobalt amount in batteries. Co is widely used as cathode material, although it has good properties in terms of lifetime and safety, several other characteristics are negative such as price, human right

[a] *Batteries Europe, Strategic Research Agenda for Batteries, 2020*

violation during mining, toxicity, and supply chain risks. Therefore, it is the aim and target of the European Commission to decrease and finally eliminate the usage of Cobalt in batteries. Newer generations such as High Energy NMC and High Voltage spinel cathodes as well as Si anodes are potential candidates to provide alternatives by increasing energy and power densities. These possibilities would be considered as Generation 3.

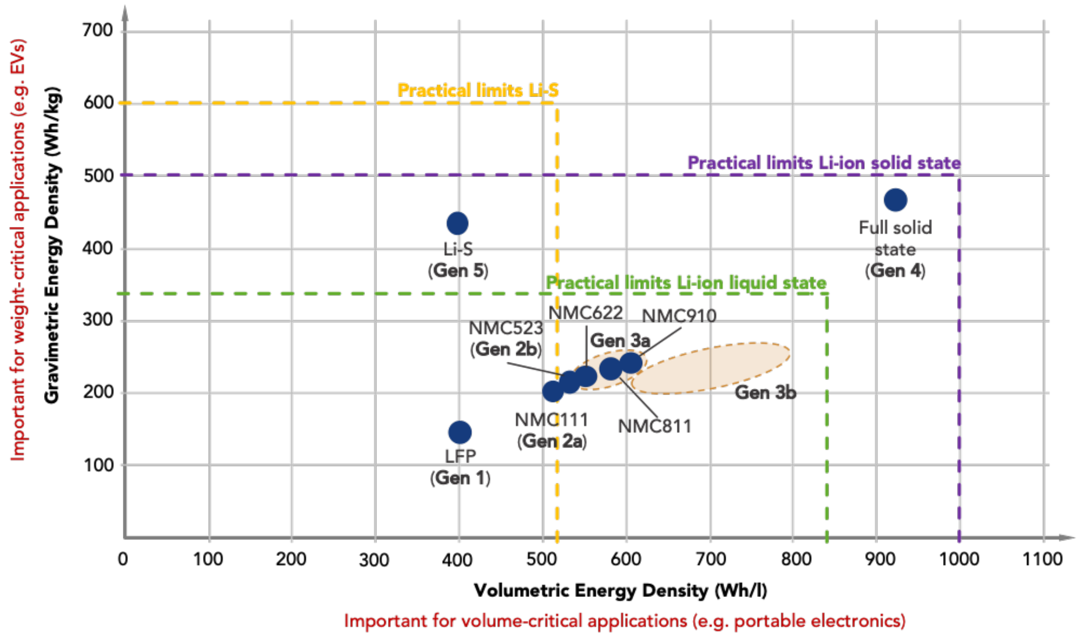

Figure 16: Current commercial batteries and targeted performance of future possible chemistries [j]

Next in generation 4 solid state batteries are considered which due to its solid electrolyte may be a safer technology. Solid state batteries have an excellent thermal stability, and the used electrolyte is non-volatile and non-flammable. Therefore, the solid-state batteries are considered safer than other Li-Ion based batteries. However, solid state batteries face other challenges, such as low conductivity at room temperature, high resistance, and still unclear compatibility of electrodes. Although the transition would start by moving from an NMC cathode and silicon/Carbon anode further improvements may come by adapting those materials. Next transition will come by the adoption of lithium metal as anode. However, this is not the last stop on the solid-state progress evolution. As generation 4c, solid electrolytes will be used together with lithium metal anodes and HVS/HE- NMC as cathode materials categorized as advanced solid-state technology. Still, better, and more sustainable materials can be in introduced, therefore the usage of air is expected in batteries by replacing NMS and HVS cathodes. Additionally, other abundant and potential materials may alto take a role like new ion-based systems.

Figure 16 shows the evolution of the different described battery generations in terms of volumetric energy density and gravimetric energy density [51]. This parameter is of great importance to be considered by the different applications. For example, mobility applications are weight and volume dependent therefore both energy density values are of great importance. For portable electronics on the contrary, the volumetric energy density is of more importance.

In Figure 17 a comparison of other energy storage technologies together with future energy storage technologies is shown and compared in terms of gravimetric energy density (Wh/kg) and volumetric energy density (Wh/l) [52]. This makes the variability and options of energy storage devices even wider ready to cover mobility, stationary or any other application.

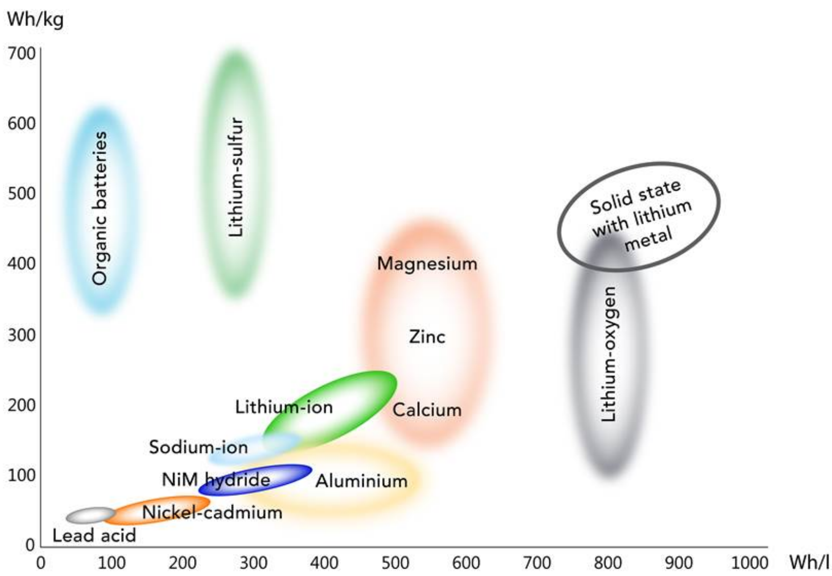

Figure 17: Characteristics and market potential of Li-ion technologies[i]

3.2.3. Digitalization & Battery Passport

- Digitalization [b]

Europe is facing multiple transitions such as the energy and the digital one. To speed up the industrialization of next coming Li Ion battery generations and shorten the time to market of the produced batteries, digital tools are crucial. The increase of usage of artificial intelligence, machine learning tools and digital twins is essential and applicable to many aspects of the battery technology. Starting with the acceleration of novel material discovery, zero defect battery production, longer lifetime, faster ageing characterization, second life feasibility, recycling adaptations and maintenance needs. It is indeed needed that the digital tools are combined with well-established data, measurements, and techniques of the state-of-the-art technology. The utilization of digital tools will facilitate the extrapolation of the technology bases towards coming generations accelerating in this way the production of novel batteries.

[b] *Batteries Europe, Strategic Research Agenda for Batteries, 2020*

- Battery Passport

The Battery Passport is a novel concept which aims to introduce standardized labels for each of the produced battery cells. The labels could be international serial numbers of QR codes imprinted in each of the cells. Using those labels, the individual cells can be tracked at each moment. The automated sorting of cells for recycling or second life purposes may be faster and safer with the implementation of the Battery Passport. Furthermore, the label can contain all needed and essential information of the cells such as: manufacturer, voltage, capacity, dimensions, weight, date of production, material content, etc. Recently, the German Federal Ministry for Economic Affairs and Climate Action (BMWK) has granted a project to develop the "Battery Pass" project[c]. Inside the consortium there are 11 partners counting with industry, research organizations and academia. The consortium is led by SYSTEMIQ GmbH and is working together with Fraunhofer IPK, acatech e.V., Volkswagen AG, BMW AG, Umicore AG & Co. KG, BASF AG, Circulor GmbH, FIWARE Foundation, TWAICE Technologies und die VDE Renewables GmbH.as subcontractor. The battery Pass will focus on gathering information such as footprint, raw material extraction, repairability and recyclability. The treated data will be securely stored and exchanged among the economic actors along the battery value chain. The aim of the Battery Pass is to focus in the next three years on: 1) Develop a technical approach for the EU Battery Passport 2) Analyse the digital software tools 3) Demonstrate the Battery Pass concept. Additionally, the project will contribute to the calculation of the CO2 footprint of a battery, to the control and assessment of hazardous substances, and will enable the improvement of batteries' life cycle impacts and costs. The battery pass is as well protected from cyber security hacks or the introduction of non-reliable data. The data is secured in a safe environment in which only credited users can access and the platform is ready to track all information in case there is a non-reliable input.

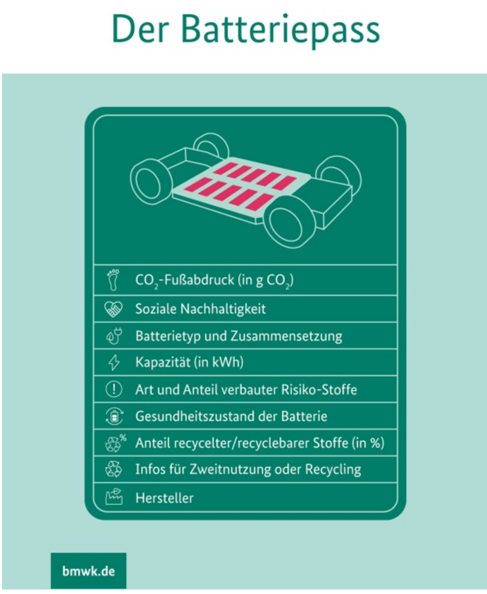

Figure 18: Battery Pass impression [1]

At European level, there is now an open call for proposal submission within the Horizon European 2023-2024 program. The call is entitled "Creating a digital passport to track battery materials, optimize battery performance and life, validate recycling, and promote a new business model based on data sharing". The deadline for proposal submission is next 5th September 2023. The granted project will be leading the battery passport concept at EU level. It is important that the Battery Passport concept should be driven by transparency of the different battery value chain steps (material, manufacturing, usage 1st life, usage 2nd life, recycling). Openness and clarity on for example the SoH and historic data, will enable more safer and more sustainable 2nd life realistic cases.

c https://www.bmwk.de/Redaktion/DE/Artikel/Industrie/Batteriezellfertigung/batteriepass.html

4. Environmental impacts of Batteries

4.1. Description of the life cycle stages and system boundaries of batteries

Batteries are a key technology to electrify the automotive sector and to support its goal towards full decarbonization. The question remains what the environmental impact is of the battery itself during its full life cycle and if there are burden shifts from one life cycle stage to another. To assess the environmental performance of a product at various points in its life cycle in a systematic manner the Life Cycle Assessment (LCA) methodology was developed. The main aim of LCA is to inform decision-makers in industry, governmental or non-governmental organizations on the environmental impacts of products and services. FIA and Green NCAP are developing an interactive LCA webtool which will inform consumers on the Greenhouse Gas Emissions and Primary Energy Demand (PED) of the vehicle(s) of choice during its lifecycle and inform consumers on pros, cons and performance of the propulsion technology of their preference. Besides sparking competition between vehicle manufacturers and informing consumers in a comprehensive manner, preventing greenwashing, also governments are informed of their national energy mixes and benchmarking the shares of renewables in the national mix. Some first static results can be found on the Green NCAP webpage[d].

Life Cycle Assessment is defined as "A technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling". The LCA framework and the main requirements and guidelines on how to conduct an LCA study are described in the ISO 14040-14044 standards [53].

In literature there are different LCA studies on batteries with varying results, mainly explained by differences in datasets, choices in system boundaries and underlying modelling assumption.

To streamline LCA of products and organisations in the EU context, the European Commission has formulated in 2013 together with its Joint Research Centre the Environmental Footprint methods [54]. The aim of the Product Environmental Footprints (PEF) is to provide reliable and comparable information on the environmental impact of a product. The PEF methods are the detailed EU recommendations on how to perform an LCA-based environmental impact assessment of a product [55]. The same document recommends developing different rulebooks on how to precisely perform product-specific environmental assessments. These ‘Product Environmental Footprint Category Rules’ (PEFCRs) are a set of specific rules that detail the more general methodological approach of the PEF guidance documents.

PEFCRs focus on the data needs, parameters and system boundaries that are most relevant for the quality of the results of a specific product category (e.g., cars, batteries, chairs, paint, …). A PEFCR for high specific energy rechargeable batteries used in mobile applications has been written [56], in which system boundaries and background and foreground datasets are defined.

This PEFCR is applicable for rechargeable single cells or/and batteries used in electric vehicles (among other applications that need batteries) and includes different battery chemistries (LCO (LiCoO2), NMC (LiNixMnyCozO2), LiMn (LiMnO2), LFP (LiFePO4) and NiMH).

[d] https://www.greenncap.com/european-lca-results/

In this document the preferred functional unit (which is the quantified performance of a product system for use as a reference unit) for a rechargeable battery is defined as 1 kWh of the total energy provided during its life. The consumption of the electricity during the use stage is included as efficiency losses during charging and discharging.

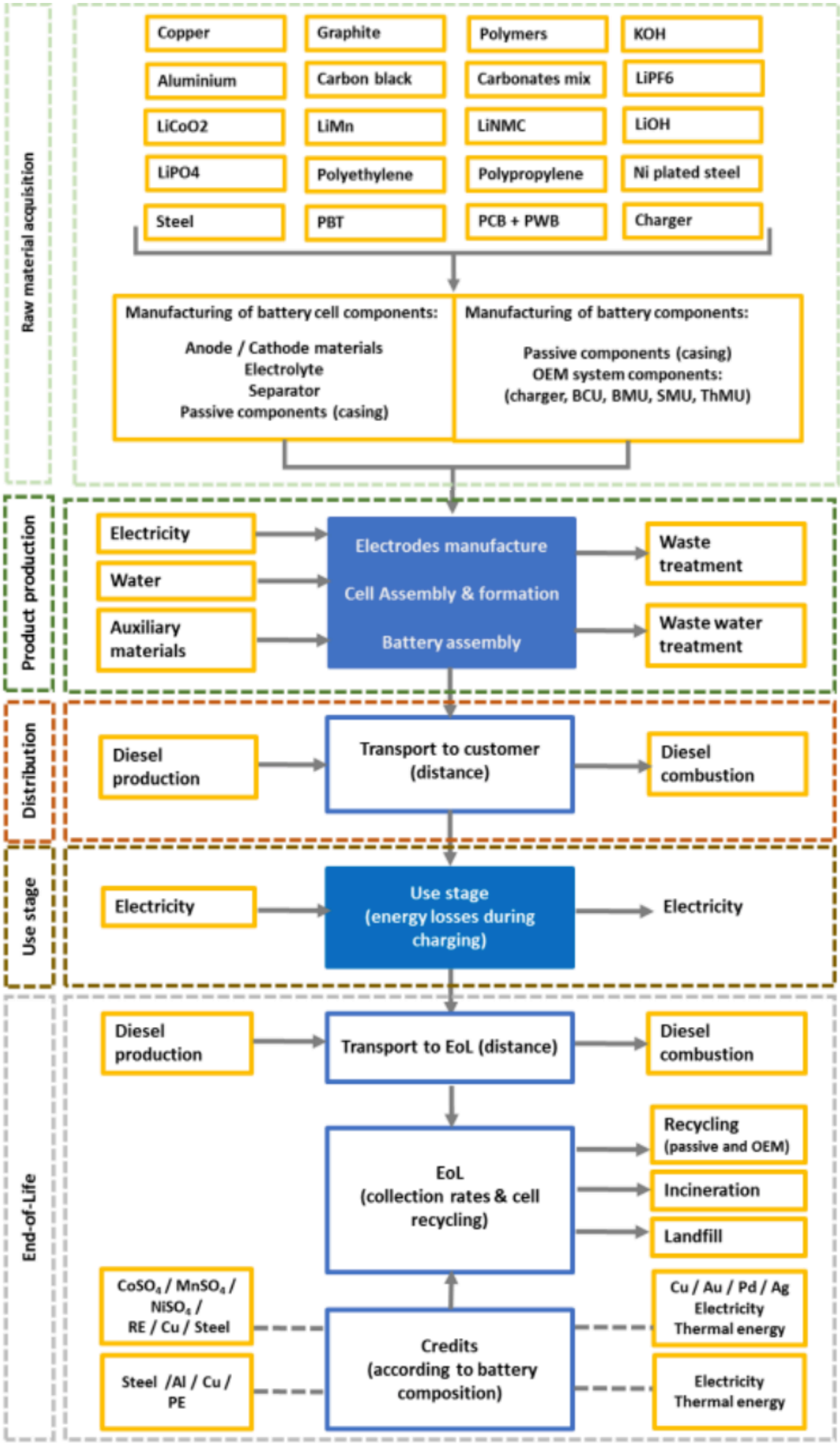

Figure 19: System Boundaries - life cycle of a battery system [56]

Figure 19 provides a general overview of the boundaries among the whole life cycle of a battery system and formulates foreground (yellow) and background (blue) data. The Life cycle stages mentioned by the PEFCR are (1) material acquisition (mining and material refining activities), (2) Main product production (consisting out of the production and assembly of the cells and the production and assembly of the full batteries pack with the casing and the electric/electronic components), (3) transport to the consumer, (4) the use stage (with the inclusion of the electricity production processes) and (5) End-of-life strategies (consisting of the collection, dismantling and recycling processes).

The production of the main product includes:

- The battery cells (composed out of its principal parts: anode, cathode, electrolyte, separator, cell container and SMU (Safety Management Unit));
- The Battery Management System, mainly including a Battery control unit (BCU) and Battery management unit (BMU);
- Thermal Management Systems (ThMU), or cooling system. Mostly consisting out of various heat exchange components (such as thermal conductive parts, tubes for circulating fluids, compressor …);
- The packaging of the modules and total battery pack.

After the raw material extraction and material refining stages the active materials are mixed with a solvent and binder and coated on an aluminium current collector (for the positive electrode) or on a copper current collector (for the negative electrode). The solvents are evaporated during a drying process. To guarantee a good electrical connection of the coated electrodes they are pressed together during a calendaring process after which they are cut to the correct size. To increase the energy content of the cell, multilayers (multiple combinations of a positive electrode, separator and negative electrode) are stacked together to create the cell.

4.1. Life cycle impact on climate change and primary energy demand of different battery technologies

Figure 20 shows the result of a review of 113 different battery LCA studies, focussing on the global warming potential (in kg CO_2/Wh) and the cumulative energy demand (in MJ/Wh) [57]. The figure shows the mean value for different battery chemistries as found in literature. The included battery chemistries are lithium iron phosphate (LFP), lithium titanate oxide (LTO), lithium cobalt oxide (LCO), lithium manganese oxide (LMO), nickel cobalt manganese (NCM), nickel cobalt manganese (NCM) and nickel cobalt aluminium (NCA). The currently most widely used chemistries for automotive applications are NMC (160 kg $CO_2/_{\text{kWh battery capacity}}$) and NCA (116 kg $CO_2/_{\text{kWh battery capacity}}$). The figure sows as well a large variability on the results. The variability is explained by ranges in the manufacturing processes (especially the electricity usage) and the exact material composition of the battery. The battery characteristics themselves play an important role as well in the carbon footprint, namely cycle life, calendric life, efficiency and energy density. The review is from 2017 and focusses on papers that are older. Resulting in carbon footprints of batteries that are higher compared to today's standards and claims by OEMS and battery producers.

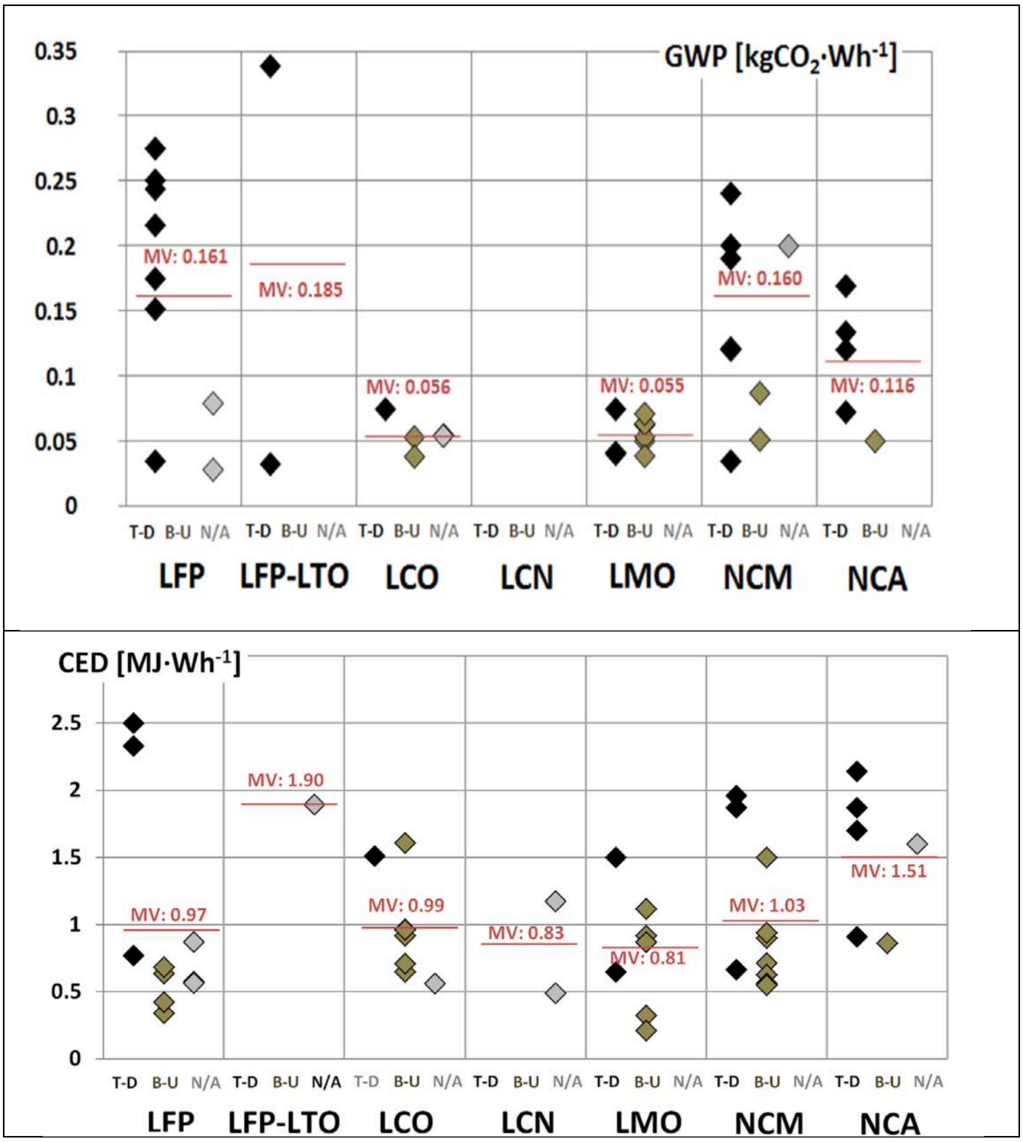

Figure 20: *Global Warming Potential (GWP) and Cumulative Energy Demand (CED) of manufacturing various Lithium battery chemistries [57]*

Although many papers are assessed it is concluded that only 7 studies contain life cycle inventories of batteries as many studies build further on the existing knowledge. There still is a need for original papers disclosing datasets of manufacturing (new) battery chemistries and their material compositions.

As currently the most widely used battery chemistries in the automotive sector are NCA and NMC a more detailed view on the environmental impacts is given for both chemistries.

In [58] the impact on climate change of a **NCA battery cell** with a high energy density (250 Wh/kg) is assessed. The anode contains with a low content of silicon and the cathode contains NCA. The life cycle inventory was obtained by full dismantling of a fresh commercial cell. Figure 21 shows the impact on climate change (123 $kgCO_2$/kWh) of the battery produced in an average plant in Korea. The production of the cooling system, BMS and the module and pack housing (aluminium production) contribute significantly to the overall impact, however, the production of the battery cell itself contributes most. During manufacturing it stands out that the electricity consumption, cathode paste and the production of the cell container contribute the most. The impact of the electricity consumption is because the manufacturing happens in Korea where two-thirds of the electricity is based on fossil fuels [59]. The production of the material the nickel sulphate material and the $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ active material contributes most to the impact of the production of the cathode paste. The impact of the cylindrical battery cell container comes most from the production of the iron–nickel alloy.

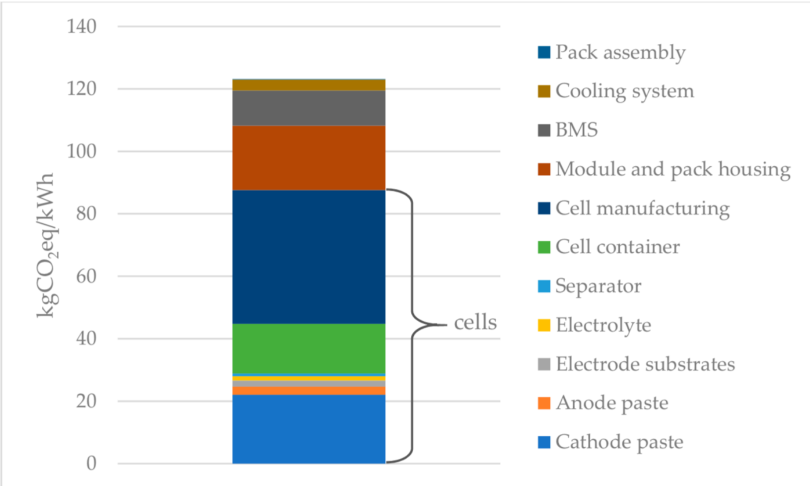

Figure 21: Life cycle impact of a NCA battery on climate change [58]

In [60] the carbon footprint of a **NMC battery chemistry** is examined in detail. Figure 22 shows the carbon footprint of the battery cell, amounting to a total impact of 163 kgCO2eq/kWh. The examined battery is a prismatic NMC622 battery, the active material in the cathode is made-up out of 60% nickel, 20% manganese and 20% cobalt. The largest contribution to climate change is during the cell manufacturing and the production of the cathode. During manufacturing the largest impact is linked to the electricity consumption which originated in this case from a German supply mix.

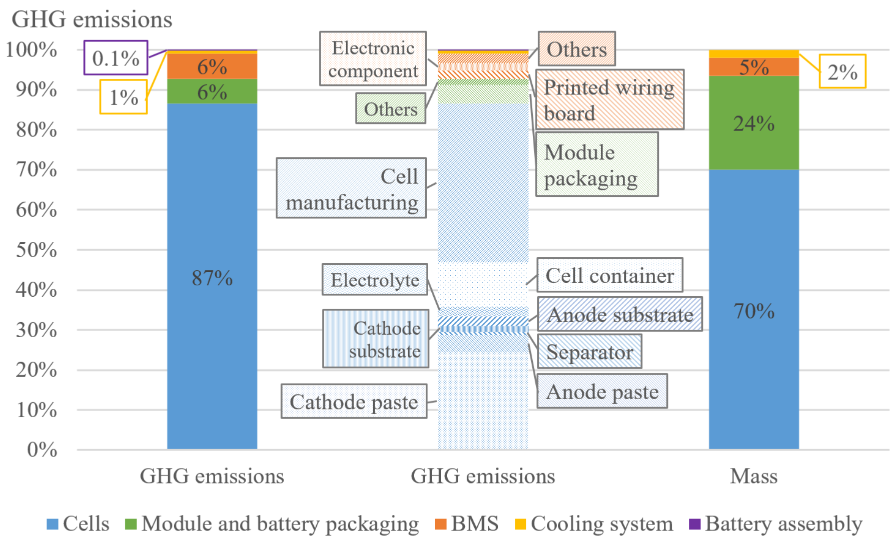

Figure 22: Greenhouse gas emissions of a NMC battery pack [60]

Figure 21 and Figure 22 should be understood as the impact of specific battery cells that are produced under specific pilot conditions, without the energy efficiency of a material optimization that is typical during mass production. Thus, the figures do not represent the impact that future batteries could have when the production processes and material content are more optimised to cut production costs and CO_2 impact.

Figure 23 shows how the eco-efficiency (expressed in climate change on the vertical axis and production cost on the horizontal axis) could be improved in the future. The blue dot represents the battery cell as discussed above in Figure 22, this battery cell was produced in Germany and as consequence the impact of the German electricity mix has been used. To optimize the manufacturing cost and the impact on climate change increasing production volumes is key, represented by the green arrow. The blue arrow indicates that the manufacturing country influences the impact on climate change a lot (based on the used electricity mixes). Battery production requires a high amount of electricity, the carbon footprint of the consumed electricity mix influences in consequence a lot the total impact. The decarbonization of the used electricity mix of a battery plant, or relocation to a country with a lot of renewable energy is a strategy that improves the impact on climate. The orange arrow shows that increasing the energy density of the battery pack significantly improves the eco-efficiency. The study concludes that it is very feasible to optimise the battery production in order to lower the carbon footprint of a battery to values around 40 CO_2 eq./kWh, which is four times lower than the base case calculated in Figure 22 [58]. At the time of the underlying study, it was an assessment of the feasibility on how to decarbonize battery production. Today some manufacturers claim to reach this potential already, however, this claim needs to be verified in peer-reviewed scientific journal articles disclosing the underlying data and models.

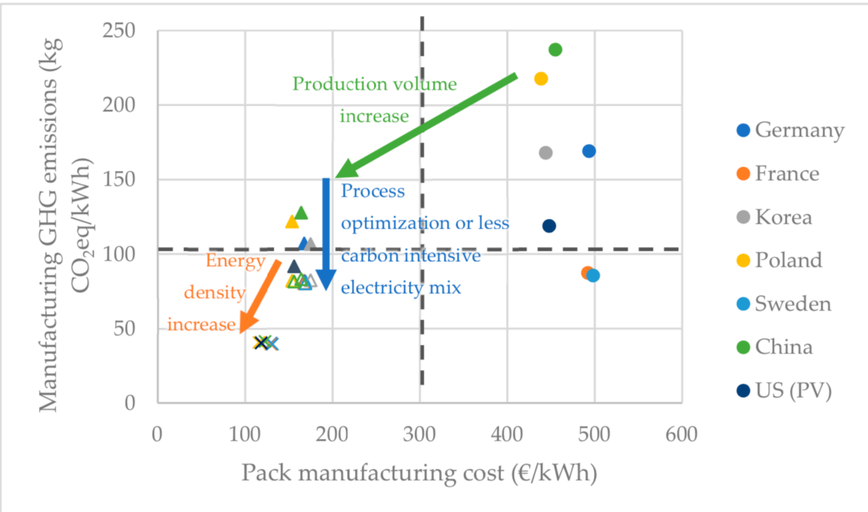

Figure 23: Eco-efficiency and reduction potential of NCA batteries [58]

4.1. Material composition and impacts to resource depletion

Lithium batteries are composed out of different materials, as many other high-tech products, some of these materials are geologically scarce and or have limitations in their supply chain. Figure 24 shows the weight distribution of materials found in the various components of an NMC battery pack [61]. Contrary to what the name suggests, lithium accounts for 1% of the total battery weight. The battery periphery (including the pack casing and the BMS) play an important role in the overall weight. However, the largest weight comes from the battery cells

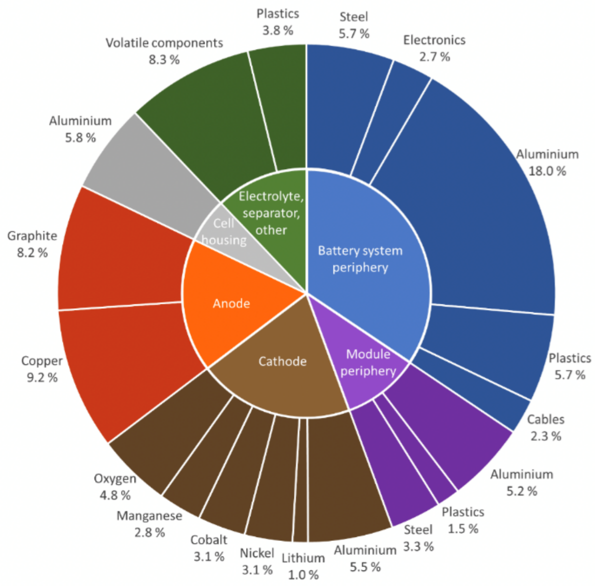

Figure 24: Generic material decomposition of a lithium battery with an NCM cathode using a weight percentage [61]

(cathode and anode, cell housing and electrolyte) themselves. Inside the cell, the cathode and anode account for the greatest weight. A NMC battery contains scarce metals such as cobalt, nickel and manganese for the cathode. Together, these three materials account for 10% of the weight. The anode is mainly composed of graphite and copper. Aluminium is used as the casing and in the cooling system. However, the weight percentage doesn't consider the criticality of the materials. Every three years the European Commission updates a list of raw materials that are critical to the EU [62]. This list is restricted to current criticality. Future trends are the topic of a foresight study. Criticality is defined by economic importance (the allocation of raw materials to end-uses in industry) and supply risk (country-level concentration of global production of primary raw materials). The list of critical raw materials that for Europe in 2020 are presented in
Table 4. The criticality of 83 materials is examined and on the list of 2020 30 materials are retained as critical.

Figure 24 show the material composition of one specific battery chemistry, namely NMC. The composition of new batteries will differ as recent battery R&D focusses on new anode and coating materials such as silicon metal, titanium and niobium. New cathodes composed out of different materials mixed together with tighter packaging, less electrolyte and thinner separators and current collectors decreases significantly the usage of scarce materials. However, as it might reduce stability, safety and durability, it raises in return the need to development of new elements to improve overall performance.

The battery materials with the largest supply risks are lithium, cobalt, natural graphite, bauxite (for aluminium production) and niobium, silicon and titanium for future generations of batteries, according to a foresight study conducted by the Joint Research Centre of the European Commission [63]. Manganese, nickel, copper have an intermediate supply chain risk. Copper is commonly used as the current collector at anode side, while aluminium is the current collector at cathode side in NCA batteries. Copper is used as well in cables in other conductive components. Aluminium is used as packaging material, for the cell, module and battery pack. Natural or synthetic graphite is used in the anode. Cobalt, manganese and nickel are used at the cathode electrode of batteries. Titanium and Silicon will be used as well in the anode in future generations of batteries. Niobium will also be used in future batteries to bring increased stability and energy density.

Table 4: Critical Raw Materials in 2020, battery materials in bold [62]

Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	**Silicon metal**
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	**Natural Graphite**	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	**Niobium**	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	Strontium

Figure 25 shows the global supply chain of batteries, including the mining, active material production and battery production. When considering the most important materials for batteries, Europe only provides 1% of the raw materials. China, Latin America and Africa produce the largest amounts of raw materials. The Democratic Republic of the Congo mines 54% of the total amount of raw cobalt, while 46% of refined cobalt comes from China. Chile, Argentina and Australia produce 90% of all lithium. When looking to processed materials China (anode materials and NMC and LCO cathode materials) and Japan (mainly NCA cathode material) are the largest producers. Europe produces only 8% of the processed materials with 18% of NMC materials and 15% of LCO materials. As all other countries combined produce only 8% of all processed materials it is not easy to significantly diversify the supply chain. China is as well the largest producer of battery cells, with a market share of 66%. As the EU has a very limited production capacity current investments are to enlarge European battery production levels. Next, the European Commission is drafting a pathway to ramp up the mining and refining of domestic raw materials. Geologically speaking, Europe has raw materials such as lithium, cobalt, nickel, graphite and manganese. Strengthening the domestic production capacity in Europe is seen as an essential part of becoming more resilient [63].

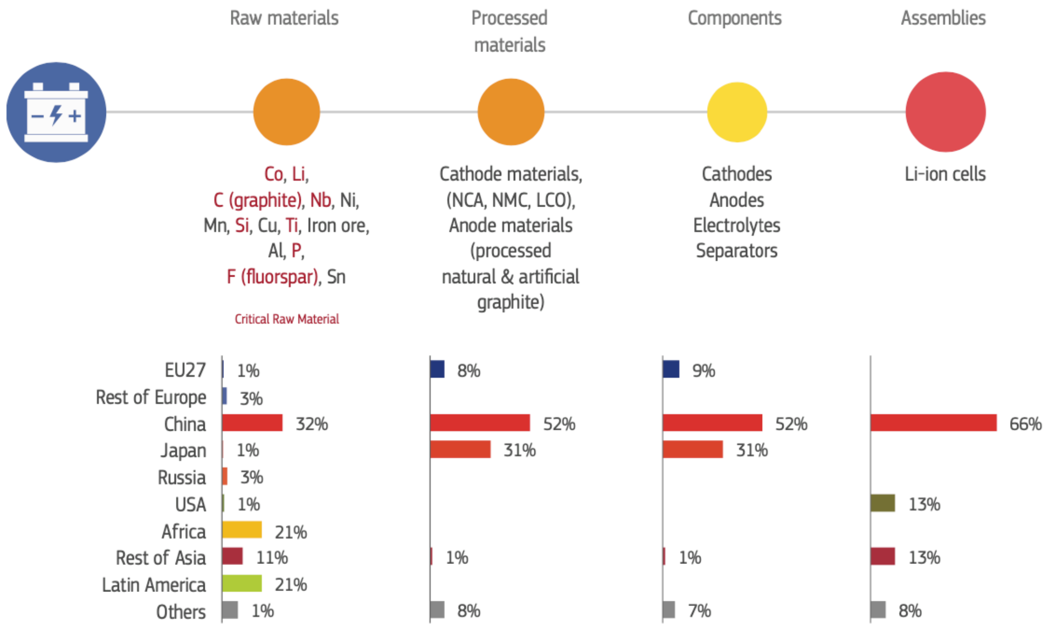

Figure 25: Lithium batteries and their supply chain risks [63]

5. Circular economy of batteries

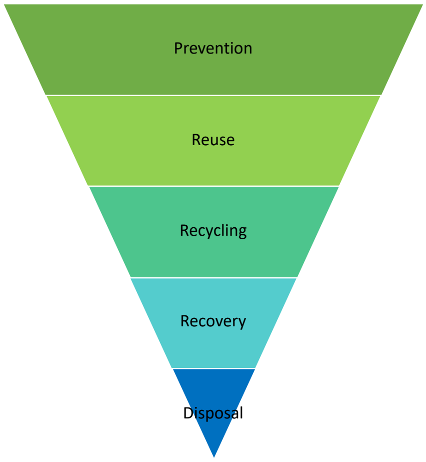

Figure 26: Waste management hierarchy

The aim of the Circular Economy Action Plan of the Green Deal in Europe is to formulate a pathway to decouple economic growth from the usage of resources. Many raw materials are today coming from outside Europe, retaining the value of these imported high-grade materials inside the EU is seen as essential to help to cover expected growth in battery demand. Increasing product lifetime, reuse of components, recycling of raw materials and the use of secondary raw materials are important parts of this plan. Figure 26 shows that recycling should be seen as a part of a larger waste management hierarchy, including reuse of products or components and recovery of energy (for instance when burning plastic and electrolyte) as well. This hierarchy was first pinpointed by Ad Lansink in 1979 and is referred to since then as 'Lansink's Ladder'. The schematic ranks the different waste management options from most to least desirable from an environmental point of view. Limiting the amount of waste that needs to be disposed and landfilled was the main environmental driver. Climbing the ladder makes the processes more complex but increases the value and amount of materials or components recovered. The hierarchy shows that recycling of materials and recovery of energy are integral parts of a good waste management strategy but should be preceded by processes optimizing prevention of material usage and re-use of the components or products. Prevention in the case of batteries would mean that new battery chemistries are developed with thinner cathodes containing less critical materials or chemistries that substitute critical raw materials by materials that are less scarce. For example, NMC811 cathode material contains much less critical materials then batteries with a NMC111 cathode. Prevention also means that car manufacturers develop lightweight city cars with smaller batteries, contrarily to today's market trend towards heavier vehicles with larger battery capacities. Re-using automotive batteries in second life (stationary) applications preserves longer the initial value of the product and its materials.

Materials that have no value should be disposed in a safe way. Newer landfilling strategies start to include as well selective deposit of specific material groups to enable future excavation and retrieval of these materials when recycling routes become more economic attractive. Figure 27 shows the different life cycle stages of batteries together with different end-of-life strategies. The typical life cycle of a battery consists out of the material acquisition stage and the main production process. During the use stage the battery is used inside electric vehicles.

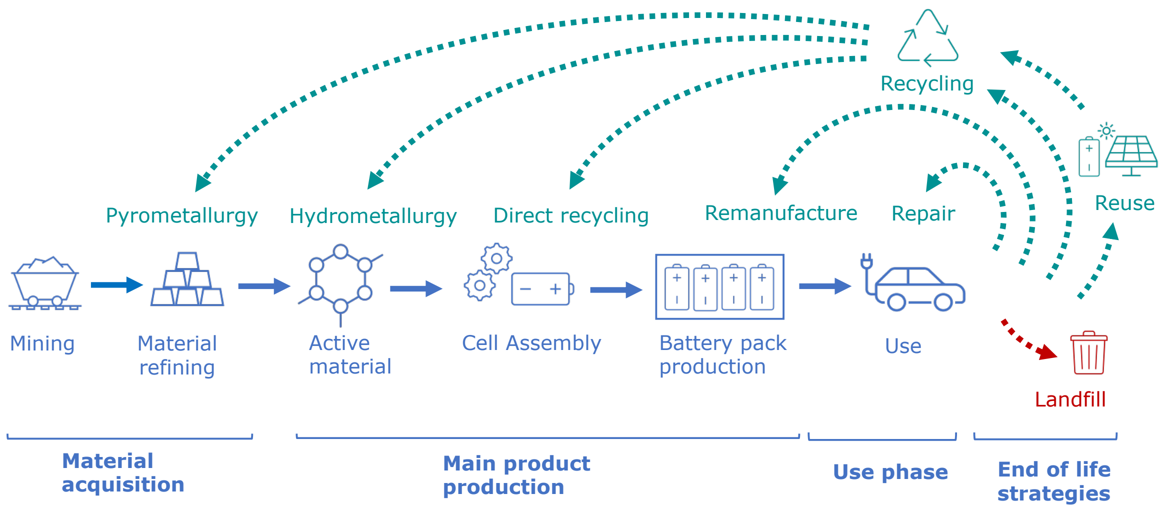

Figure 27: life cycle stage of a battery of an electric vehicle

Secondly, different end-of-life strategies emerge. Repairing the battery pack by changing defect components or models could be a good strategy to prolong the useful life of the battery and car. However, in this case proper diagnostics and safe disassembly procedures needs to be in place. When battery parts are in mint condition but should be removed from the vehicle, they could be used during a remanufacturing step inside the battery pack of another vehicle. When from a diagnosis of the battery it is clear that it should not be used anymore in a vehicle, several options exist. Landfilling of toxic and valuable materials as well as exporting chemical waste to poor countries outside Europe, should be avoided as much as possible. When batteries contain enough remaining capacity and potential lifetime, they can be repurposed into a second-life battery where they will be reused in stationary application. When reusing is not an option, the battery should follow a recycling process.

Typical recycling processes are direct, hydrometallurgical and pyrometallurgical recycling. These three techniques affect the quality of material composition in different ways, making them suitable to recover material streams or mixtures that can enter the supply chain at different stages. Direct recycling doesn't alter the material composition of the cathode, making it possible to recoat recovered active cathode material directly during the production process of a battery cell. Because of economic feasibility, direct recycling targets mainly the precious materials inside the cathode today, although research investigates the potential of using these techniques for the anode as well. Hydrometallurgy recovers material streams that can enter the production chain of active materials. Thanks to pyrometallurgy processes, basic metals such as cobalt and nickel can be recovered from waste streams. These metals can be used during the refining steps of the production chain.

5.1. Lithium Battery (LIB) Recycling processes

To lower the environmental impact, to recover valuable materials and to make Europe less dependent on imported materials there has been a growing interest in recycling, backed by battery recycling legislation. The economic viability of recycling lithium batteries is mainly determined by the value of the metal in the specific chemistries. There are various recycling processes and pathways that recover different yields of materials. The pathways can be commonly divided in preliminary and pre-treatments steps and in material extraction steps. A general overview of recycling topology can be found in Figure 28. For safe and efficient processing some preliminary steps are taken to sort and dismantle the batteries safely. Some material extraction processes need pre-treatment steps to create material fractions that can be treated in the subsequent material recovery steps. The material extraction step recovers the materials.

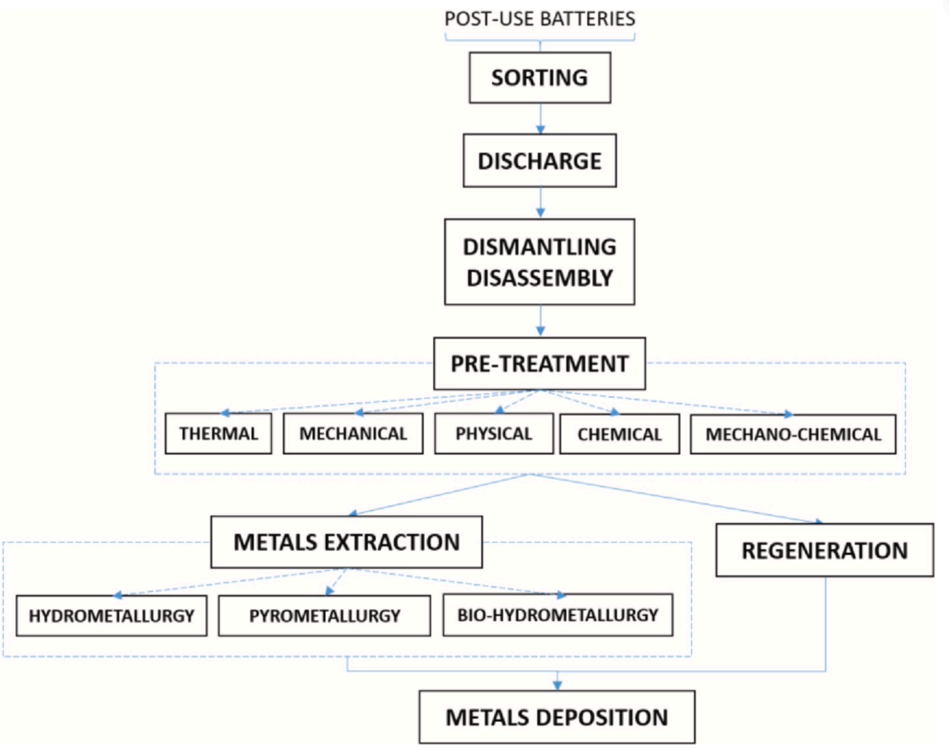

Figure 28: Recycling steps for lithium-ion batteries [64]

5.1.1. Pre-treatment techniques

The diversity of battery packs developed and used among car manufacturers is large. The industry did not go through a standardization and uniformization step yet concerning the battery pack design, size, cell shape or used chemistry. To ensure safe and cost-effective recycling, the batteries are **sorted** in their various chemistries, sizes and cell shapes. The sorting improves the purity of the recycling materials and can be done at the recycler or in a previous step during the collection. With the increasing sales of electric vehicles and End-of-Life batteries, the reverse value chain should be organized and optimized considering the logistics, location of collection, sorting and dismantling hubs.

To safely handle batteries during the recycling processes it is important to **discharge** the battery cells fully to prevent explosions, fires, or leakages of toxic gasses. To discharge the batteries, they are submersed in salt electrolyte. Other methods to discharge batteries from their residual energy is to short circuit batteries by covering them with steel chips or by connecting them to a resistor that recovers partially the energy as heat.

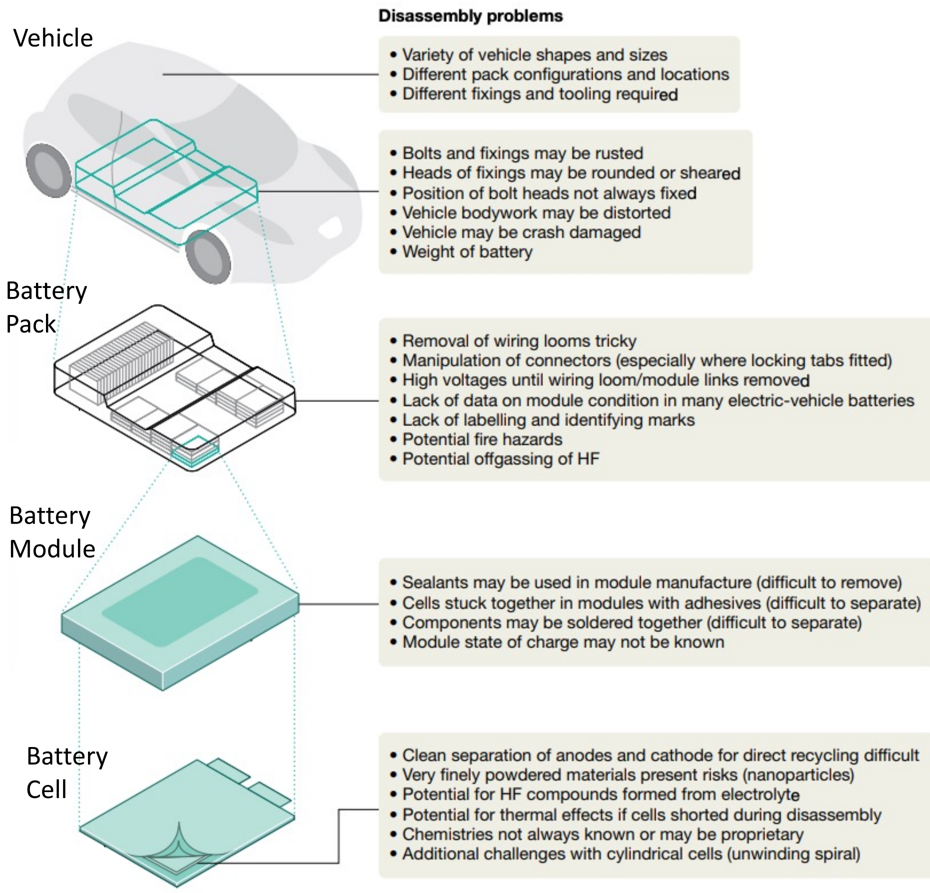

Figure 29: Challenges during disassembly of automotive batteries [7]

To improve the quality of the materials entering the material extraction processes battery packs need to be dismantled. However, automotive battery packs are complex systems composed of various components: BMS, modules, cooling system, electronics for control, cables etc This complexity presents obstacles during the dismantling of battery packs, favouring the adaptability of skilled labour over automatization. Depending on the subsequent recycling process the battery packs are dismantled into modules or cells. Battery modules can be directly recycled in pyrometallurgical processes, where plastic parts are even used as energy. Other methods such as direct recycling and hydrometallurgy need more dismantling and pre-treatment steps. Figure 29 lists the different hurdles during dismantling of battery packs and is based on the work of Harper G. et al [7]. The challenges are divided per disassembly stage: the removal of the pack from the car, the battery pack itself, the disassembly of the module and the cell. When opening the battery pack larger components can be easily separated and recovered. The copper bus bars and cables can be removed together with the electronic components and the battery modules. When dismantling modules, the plastic, aluminium, and steel components of the casing can be recovered. The electronic components and cables can be separated as well as the battery cells. The recovered battery cells should follow their specific recycling routes to recover the materials

The **pre-treatment steps** are a combination of thermal, mechanical, physical or chemical processes that create and concentrate material fractions before they enter the material extraction processes. The objective of the thermal pre-treatment process is to decompose the binder between the active electrode material and the current collector. Typical temperatures range between 250 and 600°C. To prevent oxidations of metals, the heating can be done under vacuum or inert atmosphere [64].

To increase the contact surface of the materials that needs to be recovered, the battery cells can be grinded into smaller materials fraction during a mechanical pre-treatment step. The fine particles can be afterwards classified via different physical operations into streams of more homogenous compositions. A magnetic process is used to separate ferromagnetic parts, non-ferromagnetic are further separated by sieving techniques, eddy current technology (for aluminium and copper) and air separation for light fractions. Specific chemical pre-treatment steps are used to recover electrolyte, binder or solvents.

5.1.2. Existing LIB recycling methods & innovative processes

After the pre-treatment steps, the materials can be recovered by pyrometallurgy or hydrometallurgy processes (or a combination of both). **Pyrometallurgical** recycling consist out of different high-temperature steps, complete battery modules or cells are often directly fed into the process excluding the need for pre-treatment. During high temperatures (± 1500 °C), the high-value metals are melted out of the batteries. The metal alloy coming out of this process contains usually cobalt, nickel, copper and iron. During the incineration many battery components and materials, such as the anode, electrolyte, plastics, are to fuel the process and are inherently lost. Typically, the slag contains aluminium, manganese and lithium. Often these materials will not be recovered. The advantage of pyrometallurgical recycling is that it is a simple procedure that is fully developed. Different chemistries can be processed together and there is little need for pre-treatment. However, many materials are lost during this expensive and energy intensive process. Energy intensive processes, depending on the energy sources, are often as well processes with intensive greenhouse gas emissions. In the case of recycling, these direct emissions are being offset with the emissions linked to the avoided processes for the primary material production, which is most often a much more energy intensive process.

Hydrometallurgy can recover many more materials but needs more pre-treatment steps to generate the material streams that can be processed. During hydrometallurgy the valuable materials are extracted by leaching them with inorganic acids. This process enables to recover aluminium, lithium, manganese and graphite. An eco-friendlier, experimental version of the process uses inorganic acids from bacteria and fungi. The advantage of hydrometallurgical recycling is that many materials are recovered with a high purity. It is a well-developed procedure that needs less energy and pollutes less then pyrometallurgy. However, the drawback is that it is a more complex procedure that needs specific pre-treatment techniques and selective inorganic acids per battery chemistry.

Direct recycling separates at the cathode the active material from its current collector, after which the material is mixed and reactivated. The regenerated cathode material can have performance and characteristics that are very similar to newly produced material (Chen *et al.,* 2019). The advantage is that active materials keep their value and can be directly reused as new electrode coatings during the cell manufacturing process. Via this procedure more materials can be recovered compared to pyro- and hydrometallurgical recycling. The drawback is that direct recycling is not yet developed as commercialised technology and it requires intensive pre-treatment steps as it is sensitive to the quality of the input material streams. Figure 30 summarizes the comparison of the three main recycling processes.

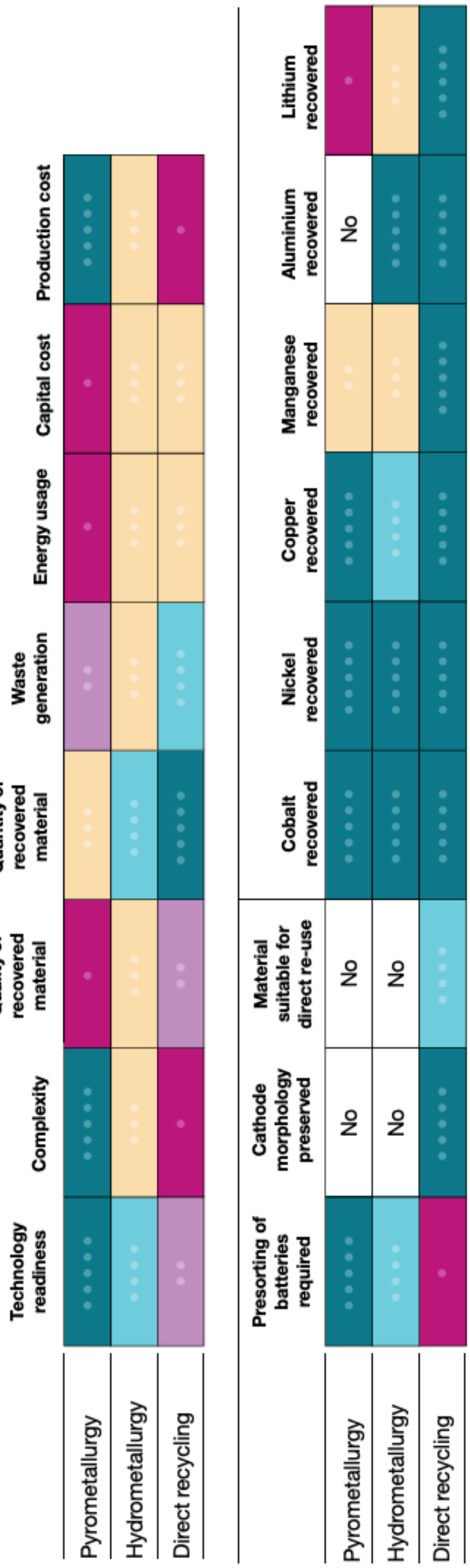

Figure 30: Comparison of pyrometallurgy, hydrometallurgy and direct recycling, with green best and red worst [7]

To increase the economic and environmental viability of recycling new innovative recycling processes are being developed. Currently the economic viability of recycling is influenced by the amount of valuable cobalt that is in the cathode of the battery cells. As there is a trend to lower or abandon cobalt in batteries, new recycling processes need to be developed. Following developments help to increase the recoverability of materials. Design for circularity, disassembly and/or recycling of battery pack is a must. Not all battery pack are easy to disassemble and the design can be optimized for easy deconstruction. Better sorting techniques and recognizing battery chemistries would help to pre-sort material streams and reduce the need for complicated processes. The Battery Recycling Committee of the Society of Automotive Engineers (SAE) have developed a battery label for easy recognition of battery types (Pb-acid, Ni-MH, or Li-ion). This is a first step in better sorting of cells, but it could be extended with more information on precise chemistry, origin and state of health, such a data sharing platform is referred to as a battery passport by the Global Battery Alliance.

Today, sorting and disassembly are intensive and skilled labour jobs. Integrated innovation involving automatization, robotics and artificial intelligence could improve these pre-treatments steps significantly. For safe handling of battery cells, discharging them early in the pre-treatment step is important. A cost-effective innovation could investigate how to optimize energy recovery during this discharge step.

Other novel R&D efforts look how to extract materials that today are lost (for example the separator, the electrolyte). Pyrometallurgy and hydrometallurgy are mainly focused on recovering the most valuable materials from the cathode of NMC battery. Novel methods for separating active electrode materials embedded in LMO and LFP for direct recycling are under investigation.

5.2. List of potential business opportunities

In this paragraph a non-exhaustive list is given about potential business opportunities when moving from a traditional to a circular value chain. The value of the transition towards circular economy could mean in the best case the improvement of environmental, social as well as economic values. The objective of circular economy is in this section understood as maximising the service delivered by a resource along its entire value chain. This might mean using less material while delivering the same service (for example, using an NMC811 battery instead of an NMC111 one) or intensifying the usage of the products and/or services (for example, using the battery and vehicle more intensively through its life thanks to a car sharing service) that are constituted out of those materials.
Figure 31 shows some business opportunities in the value chain of electric vehicles and is adapted from a report from the World Economic Forum [2]. Battery electric vehicles are coupling three different sectors, namely the battery producers, the power production and the car manufacturers, that were not coupled in the past.

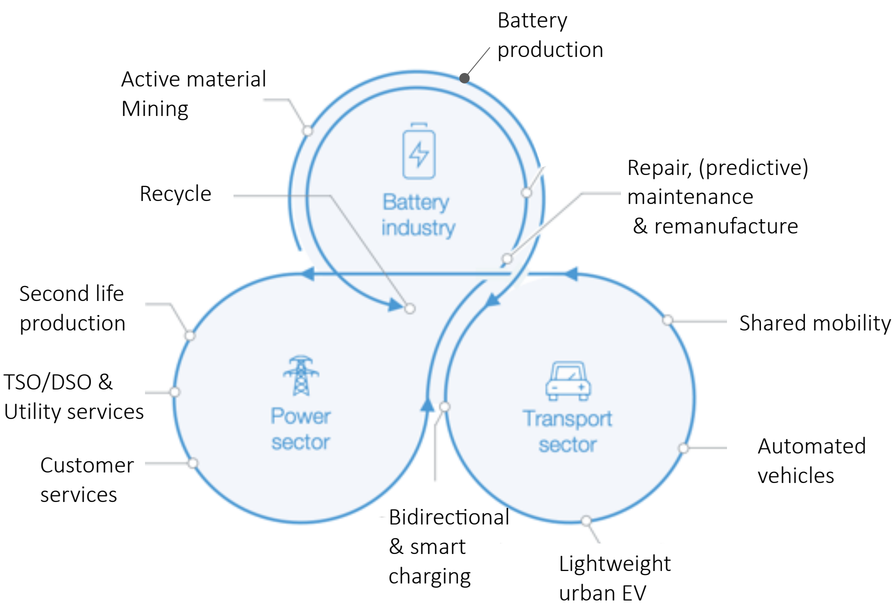

Figure 31: Business opportunities along the value chain of electric vehicle batteries, adapted from World Economic Forum [2]

- Opportunities in the battery supply chain

Figure 32 shows the expected growth in demand and supply of the supply chain of batteries in Europe [65]. The expected demand in 2030 is 1000 GWh. In blue the share of the expected European supply is given, subdivided in mining of raw material, production of active materials, battery manufacturing, the integration in the application and the recycling and second-life processes. Europe has many OEMs that focus on integrating batteries in their applications. Battery manufacturing inside Europe has been non-existing but is expected to grow substantially in the coming years until 2030.

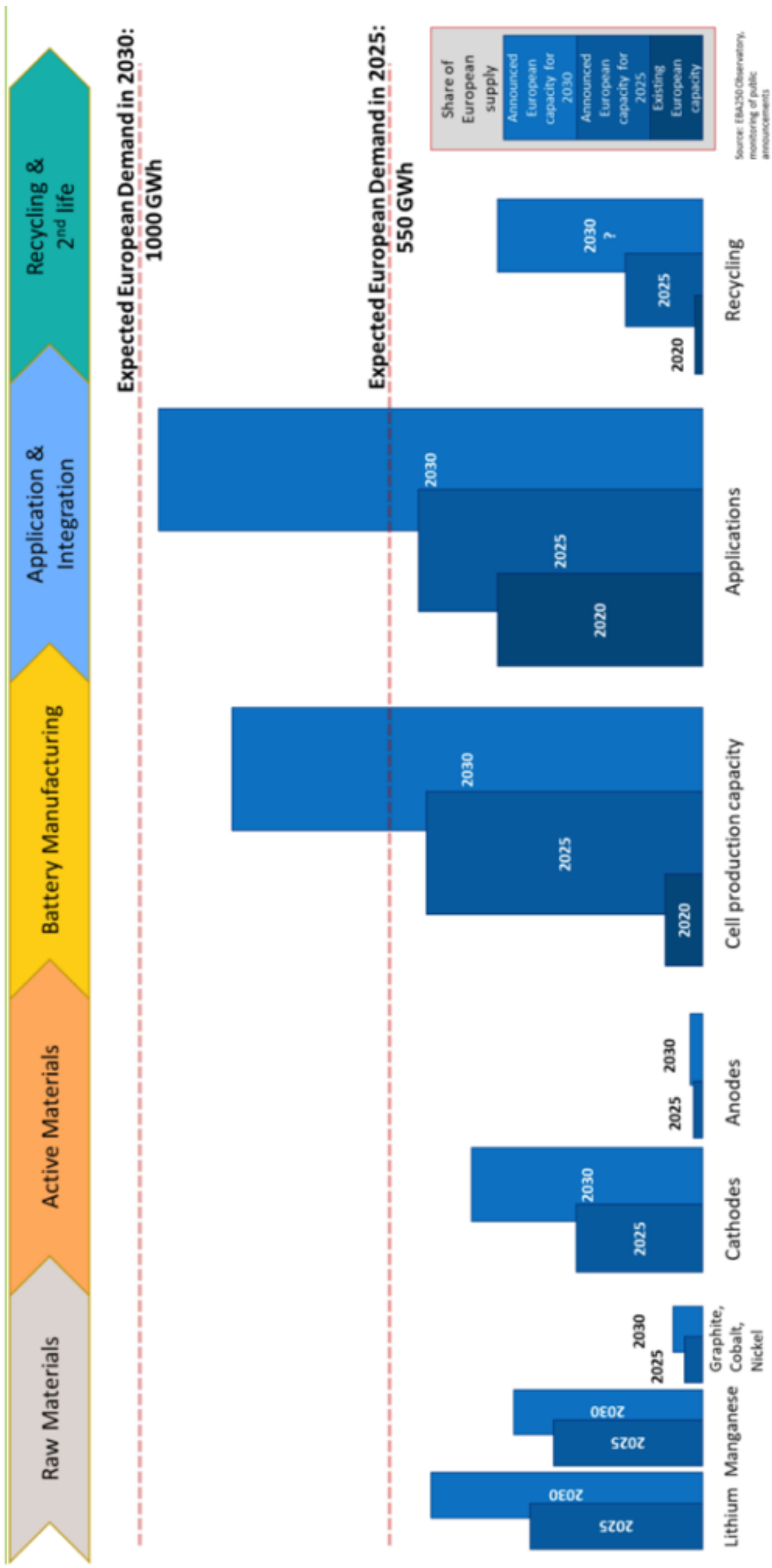

Figure 32: Growth of battery demand and supply in Europe, from 2020 to 2030 [65]

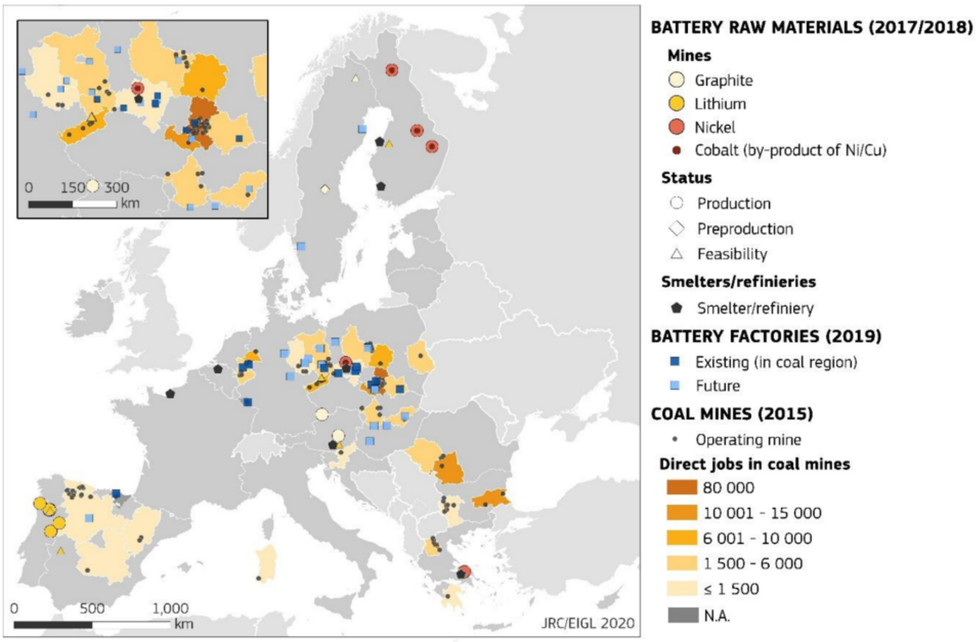

Figure 33: European mines for battery raw materials (left top rectangle zoom shows partly Germany, Poland, Czech Republic, Slovakia and Austria) [62]

Mining critical raw materials in Europe is seen as an essential part for the EU to become more resilient. Figure 33 shows the geological distribution of graphite, lithium, nickel and cobalt in Europe. Europe has significant amounts of critical of raw materials, however, lacks public acceptance and trust on environmental and social impacts related to mining activities. On the other hand, reopening former coal mines and/or recovering critical minerals from historic mining waste could create economic growth in regions that are/were depending on coal mining.

Figure 34 provides a view on the substantially growing European battery production capacity. Ten of these battery production companies have a headquarter in Europe and will start production in the coming years: ACC (France and Germany), CELLFORCE (Germany), Eneris/Leclanché, FAAM/LITHOPS (Italy), INOBAT (Slovakia), MES (Czechia), NORTHVOLT (Sweden), VARTA (Germany), VERKOR (France) and VOLKSWAGEN (Germany) [62].

Figure 34: Location and listing of European production capacity of batteries [4]

- Opportunities in the transport sector

The transport sector has the opportunity to develop new services that intensify the usage of the material inside their products. Several examples of these opportunities are listed below. The capacity of the batteries inside electric vehicles has increased significantly throughout the years (for example, the first Nissan Leaf on the market had a 24 kWh battery while the current version is equipped with battery up to a 60 kWh) as a result of decreasing battery production costs and customer expectations to have a driving range up to 500 km. However, it is clear that the capacity of these battery is far beyond what is strictly need for daily commuting distance. How to optimize this idle battery capacity and underusage of the embedded scarce materials? Coupling the transport and power sector brings a great opportunity in the effective use of scarce resources. On one hand electric vehicles need to be charged, which poses, with increasing electrification, challenges for the power sector. How to deliver the needed energy to power large charging hubs? On the other hand, the power sector itself is going through a full transition towards decentralized energy production with renewable, intermitted resources. Renewable energy such as wind turbines and photovoltaics create an unbalance that needs to be met with storage capacity and flexible consumers. When electric vehicles are plugged in the grid, their batteries can be used to support the electricity grid. As vehicles are parked longer per day than that they are driving, they can also be seen as flexible consumers that can be charged at the most convenient periods and participate in various flexibility markets of the transmission or distribution operators. Integrating smart charging or bidirectional charging can create additional revenue for the owners of the vehicle and allows higher integration of renewables in the energy system.

Shared mobility can intensify the usage of vehicles and their valuable batteries, enabling the effective use of these assets. Higher daily driven distances with multiple users would need a redesign for longevity of the hardware and the user-friendliness of the sharing service. In a mobility service the user isn't anymore the owner of the battery, providing opportunities to the service operator to efficiently manage the usage, (predictive) maintenance and the repurposing of the batteries from their vehicle fleet.
Repairing the battery can intensify the usage of the resources embedded in electric vehicles by extending their useful life. To enable repairability, the maintenance shop needs access to onboard diagnostics to verify battery life and needs to be able to locate and exchange failing components (for example a faulty battery module). Degraded or faulty battery modules can be examined further to decide if they can be repurposed in another application or should follow a recycling process to recover the materials. Obviously, the battery can only be repaired if this has been considered and applied during the design process. The propulsion battery diagnostic functionality should be transparent to authorised service providers and be made available at reasonable cost. At the same time, the propulsion battery systems should be designed for security and safety as well, over the lifetime.

- Opportunities in the power sector

When end-of-life batteries are removed from electric vehicles and are diagnosed and certified as safe and with a useful remaining capacity, they can be repurposed in other applications. Repurposing batteries recovers the residual value of the battery and accelerates the usages of battery storage in other sectors. Repurposed batteries can be used in stationary applications to bring services to the transmission and distribution operators or to private customers. Various battery sizes can be examined for second-life applications.

Figure 35: Example of grid services delivered with repurposed BMWi3 battery packs

In some cases, where larger battery capacity is needed, the battery packs of electric vehicles are not dismantled but fully reused with their original casing, cooling system and battery management system. In the example in Figure 35 many BMWi3 battery packs are clustered and controlled together to support the electricity grid. Some BMS systems can disconnect faulty modules or cells from a software perspective.
In other cases, the battery pack is dismantled at module level of cell level and tested before the new battery pack is composed and rebuilt. With more dismantling the labour cost increases, and the repurposed battery will need new customized components such as a casing, cooling circuit and battery management system, adding to the final cost of the second-life battery. Stationary lithium-ion batteries can provide various services to the

electricity system as a whole. Four major groups are distinguished, some of these services can be stacked together:

1. **Energy Arbitrage:** This type of service dispatches blocks of energy from one moment to another. The battery is charged at moments when the energy price is low on the wholesale market and discharged at the moments when prices and demand are higher.
2. **Capacity credit:** Batteries are used at different location in the transmission or distribution infrastructure in order to delay or reduce new investments to reinforce the grid locally. Introduction of distributed renewable energy production can yield the need for local reinforcement of the grid. Grid connected storage can help to smoothen the peak power at bottlenecks in the grid.
3. **Ancillary services:** Batteries have a fast response time and can help with voltage and frequency regulation by controlling active and reactive power and mitigating frequency variations.
4. **Behind the meter:** Batteries can provide customer side benefits such as decreasing the electricity bill by changing the timing of consumption to off-peak tariffs, increase the self-consumption of Photovoltaic (PV) installations by charging the battery at moments that there is an excess energy production and can act as backup power units for critical installations.

6. Standardization

6.1. Safety issues and challenges related to lithium-ion batteries

6.1.1. Battery materials and components

The hazards associated to battery technology depends on the used materials of the cell composition. Therefore, it is important to understand which kind of components are needed in a Li Ion battery. A Li ion battery is composed of two electrodes (anode and cathode), a separator and electrolyte.

The anode and the cathode are the electrodes where the lithium ions move, from one side to the other and vice versa. Numerous cathode materials can be used as cathode materials, such as LMO, LCO, NCA, NMC or LFP. Differences between the cathodes can be found, such as the safe characteristics of LFP cathodes due to its thermal stability (reaching thermal runaway at higher temperatures in comparison to other materials) and non-toxicity. Regarding the anode, carbon is the most used one, but lithium titanate (LTO) has also been recently used. LTO is a good candidate in terms of safety, long cycle life however cost is the biggest drawback of this material.

The separator prevents electrical contact between anode and cathode while at the same time allowing ion transport. The most used separators are made of thin microporous polyolefin membranes made of poly- propylene (PP), polyethylene (PE), or laminates of both (e.g., PP/PE/PP). For the separator the melting point is of great importance, for PE at 135 °C and for PP this is 165 °C showing stability at higher temperatures. Ceramic separators are also used showing high temperature stability, wettability, and good chemical resistance.

The electrolyte is the medium where all components are fully soaked in. The electrolyte is based on organic solvents which are frequently highly flammable [66].

The most used electrolytes are mixtures of dissolved salt (e.g., lithium hexafluorophosphate ($LiPF_6$)) and various carbonates (e.g., propylene carbonate). In the event of thermal runaway, a process of consecutive events may occur, such as electrolyte decomposition, formation of gases, overpressure, venting, rupture, release of toxic gases. Thermal runaway may lead to an uncontrolled, self-increasing temperature that eventually destroys the battery due to exothermal reactions of battery components. Flammability may also happen, however there are additives to be used which will delay the hazard reaction. There are other electrolyte alternatives which are proved to be safer, ionic liquids [67] and high flashpoint electrolytes [68]. Both are thermal and chemically stage, and their flame resistance is higher than the previous. Other electrolytes can be in gel/liquid form, where safety is improved due to the absence of risk of electrolyte release and the lower reactivity versus lithium [69]. However, their ionic conductivity is much lower than in a liquid electrolyte.

The binder is responsible to enable the electrode fabrication. To fabricate the anode, polyvinylidene fluoride (PVDF) is needed. However, styrene butadiene rubber (SBR) is also used due to the flexibility that provides to the anode. With higher flexibility, higher binding ability larger capacities and higher cyclability can be reached. For cathode fabrication SBR is not suitable due to their oxidation problem, therefore PVDF is widely used. For dissolution PVDF requires N-methyl pyrrolidone (NMP) which is toxic. Hence, water soluble binders are an alternative to PVDF. Other alternatives such as acrylate-type copolymer are coming in place [70].

Li Ion batteries require different components who may lead to different hazards. To improve the safety level of a battery, it is important to understand and evaluate all different parameters. Moreover, to be able to achieve a safe application system, the selection of the cell components based on cost performance and safety is essential.

6.1.2. Battery cell and pack design

It is estimated that, if a proper safety control is in place, the probability of cell failure during normal operation is one in 40 million [71] or less optimistically one in 10 million [72]. Although the probability is quite low, the consequences may be of importance. Accordingly, safety measures to increase the battery safety are always under discussion and research. Starting from individual components and used materials, cell format, smart control strategies, and installation and usage requirements and limitations [73].

It has been already described that each single cell behave differently therefore it will have a different ageing history creating more difference between the rest of the cells. Therefore, it is of great importance, to implement a proper cell balancing system to avoid any hazardous situation. Additionally, ageing and SoH should be closely monitored and estimated not only to control the correct usage of the battery in a certain application but also to enhance and enable possible second usages of the batteries at lower SoH levels. For a possible application exchange, understanding the history and SoH status of the battery is crucial. Furthermore, cell design as well plays a critical role determining the safety procedures to follow of the full battery. Single battery cell formats vary from cylindrical, prismatic and pouch (figure 4). All formats are widely used in e-mobility applications, however each type has its own pros and cons.

Cylindrical cells are mechanically robust, are not costly to manufacture but their packaging efficiency is low. Swelling during operation may not happen in this type of cells however high pressure build up may lead to the rejection of the jelly roll, where the anode, separator and cathode sheets sit [74]. They are known to be used in Tesla vehicles. Prismatic cells have a good mechanical stability, and the packaging is highly efficient, but they are more costly to manufacture [75]. Gases may be released through a vent in a high battery-internal pressure event. However, sometimes this vent may be too small or may get clogged to release the gas, thus cell fracture or explosion may occur [76].

Prismatic cells are widely used in Audi, VW, Porsche, Fiat, Peugeot, Citroen vehicles. Pouch type cells are very frequently used in research activities due to its simple method to assemble. This type of cells is flexible, light, not very costly and they have the higher energy density. On the negative side, due to their light and flexible packaging, for protection issues more robust pack system and caging are usually needed.

Even though pouch cells are prone to swelling, they have no venting mechanics since the sealing of the cells applies low resistance to high pressure. Thus, the release of gasses happens already at smaller energy scales. In a thermal runaway event, pouch cells may be safer as they are mechanically weaker and can release build-up pressure more softly compared to cells with a hard case [77]. Pouch cells are commonly used in Renault, Mercedes and Mini vehicles.

6.2. Technical Standards and international, legally binding Regulations

Certification of lithium-ion batteries is mandatory for further usage of the battery in a specific application such as an electric vehicle. The presented international standard and regulation overview is related to the abuse tests to be developed for Li ion battery based electric vehicles. Specific tests for mechanical, electrical, environmental, and chemical abuse are described in the standards and regulations. Mechanical tests, mechanical shock, drop, penetration, immersion, crush/crash, rollover, and vibration tests are considered. External short circuit and overcharge/over discharge are part of electrical tests. Environmental test covers thermal shock and cycling, overheat and fire tests. Emission and flammability are considered chemical tests. The selection presents a currently valid overview focused on what is applicable to the full pack and sometimes vehicles level.

Technical Standards:
The current safety standards for a battery used in an electric vehicle application are the following:

- SAE J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing. 2021 [78].
- SAE J2929: Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells. 2013 [79].
- ISO 6469-1: Electrically propelled road vehicles - Safety specifications Part 1: Rechargeable energy storage system (RESS). 2019 [80].

There are as well other more specific standards for some specific tests. This is the case for the vibration test where the following two standards are also valid and in place.

- IEC 60068-2-64: Environmental testing Part 2: Test methods - Test Fh: Vibration, broad-band random (digital control) and guidance. 1993.
- SAE J2380: Vibration Testing of Electric Vehicle Batteries. 2021

Another important safeguard is provided by the Euro NCAP bulletin [81] regarding testing of electric vehicles. The Euro NCAP organisation develops whole vehicle protocols that go beyond legal requirements and associated performance criteria. These protocols are endorsed by vehicle manufacturers of which the vehicles comply with on a voluntary basis.

Following the case of automotive applications, via the use of EUCAR hazard levels [82,83] an abusive condition can be sorted. Industry regularly use this classification to evaluate their applications in an abusive condition. EUCAR hazard levels are categorized from 7 to 0. Where 7 indicates the highest hazardous situation such as explosion, and 0 level represents that the system has no hazard and operates normally. An acceptable level corresponds to a level 3 or lower.

Legally binding regulation:

Technical regulations referring to the approval of vehicles with regard to the electric power train as well as the approval of vehicles about protection of fire risks are already in place:

- UN/ECE Regulation No 100.03: Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train. 2013 [84].
- UN/ECE Regulation No 34.03: Uniform provisions concerning the approval of vehicles with regard to the protection of fire risks, 2015 [85].

Fire risk mitigation is a topic of high relevance and importance to the automotive industry, in which relevant research work has been already done and is still ongoing [86,87,88].

Additionally, there are several international, legally binding regulations in place focusing on the approval of the vehicles regarding protection of the occupants/driver in the event of a certain impacts.

- UN/ECE Regulation No 95.05: Uniform provisions Concerning the Approval of Vehicles with regard to the protection of the occupants in the event of a lateral collision. 2011.
- UN/ECE Regulation No 94.04: Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision. 2012.
- UN/ECE Regulation No 12.04: Uniform provisions concerning the approval of vehicles with regard to the protection of the driver against the steering mechanism in the event of impact. 2012.

To finalize with the standard and regulation overview, it is as well important to highlight that a world-wide applied regulation on the transport of dangerous goods such as Li ion batteries is in place since 2015:

- UN 383: Recommendations on the Transport of dangerous goods Manual of test and criteria 6th revised edition. 2015.
- UNECE Global Technical Regulation No 22 on battery durability [89].

6.3. EU Battery Regulation

The General objective of the Commission's EU Battery Regulation proposal [90], replacing the previous battery directive (2006/66/EC), is to strengthen battery sustainability throughout their life cycle, by ensuring minimum sustainability requirements for batteries placed in the EU internal market. Increasing the resilience of the EU battery supply chain by closing the materials loop. Reducing the environmental and social impacts throughout all the stages of the life cycle of batteries. The specific objectives can be summarized as follows:

Objective 1: Strengthening sustainability

- Foster the production and placing on the EU market of high quality and performing batteries.

- Develop and use EU battery raw materials potential, both primary and secondary, ensuring they are produced in an efficient and sustainable way.
- Ensure functioning markets for secondary raw materials and related industrial processes.
- Promote innovation and the development and implementation of EU technological expertise.

Objective 2: Increasing resilience and closing material loops

- Reduce EU's dependence on imports of materials of strategic importance.
- Ensure appropriate collection and recycling of all of waste batteries.

Objective 3: Reducing environmental and social impacts

- Contributing to responsible sourcing
- Efficient use of raw and recycled materials,
- Reduce GHG emissions across the entire life cycle of batteries.
- Reduce risks for human health and for the quality of the environment and improve social conditions of local communities.

To track the progress of reaching the desired objectives following indicators are put in place.

- Increased quality of batteries placed on the market;
- Better recycling efficiencies and better material recovery for Ni, Co, Li and Cu
- Higher degrees of recycled materials in batteries;
- More batteries will be collected and recycled;
- Industrial and EV batteries will be counted, tracked and reported;
- All collected batteries will be recycled; recycling processes will be performant at reduced occupational health and safety risks;
- End-users will have better and easier access to information on the batteries they buy in terms of materials they contain, their expected durability, and how their production meets environmental and social standards;
- All industrial and EV batteries have their CO2 footprint calculated;
- Manufacturers of industrial and EV batteries, will also provide information on how their materials sourcing meets social responsibility criteria;
- Battery manufacturers will have a clear and predictable EU legal framework that supports them in innovating and being competitive in a growing market

In

Table 5 a summary is provided of the EU Battery Regulation proposal and its targeted measures. It is indicated if measures have an impact on the electric vehicle industry (in green) or when they are not related (in grey). As a summary, the new EU battery regulation proposes to include a battery passport (#12), a carbon footprint declaration (#6), increase the recycling and material recovery targets (#5, #9), increase the collection rate (#4), define some responsibilities (#10, #13), establish performance and durability (#7) and set up definitions (#1, #2). Each of these requirements will need to be in place at different dates. The adoption scheme of the Battery regulation proposal can be retrieved from the following timeline https://eur-lex.europa.eu/procedure/EN/2020_353

Table 5: Summary of most relevant recommendations from the EU Battery Regulation

#	Measures	Recommendation from the EC	Related Article	Related Annex
1	Classification and definition	New category for EV batteries Weight limit of 5 kg to differentiate portable from industrial batteries	Article 2	
2	Second-life of industrial batteries	At the end of the first life, used batteries are considered waste (except for reuse). Repurposing is considered a waste treatment operation. Repurposed (second life) batteries are considered as new products which have to comply with the product requirements.	Article 5 (EoL requirements) Chapter VII (EoL management)	
3	Collection rate for portable batteries	65% collection target in 2025 70% collection target in 2030		Annex XI
4	Collection rate for automotive and industrial batteries	New reporting system for automotive, EV and industrial batteries	Article 49	
5	Recycling efficiencies and recovery of materials	Targets lithium-ion batteries and Co, Ni, Li, Cu. Recycling efficiency of lithium- ion batteries: 65% by 2025, 70% by 2030. Material recovery rates for Co, Ni, Li, Cu: resp. 90%, 90%, 35% and 90% in 2025, resp. 95%, 95%, 70% and 95% in 2030	Article 56 Article 57	Annex XII (Treatment and recycling)
6	Carbon footprint for industrial and EV batteries	Mandatory carbon footprint declaration. Carbon footprint performance classes and maximum carbon thresholds for batteries as a condition for placement on the market. The timeline for the three requirements is 1 July 2024 for the carbon footprint declaration, 1 January 2026 for the performance classes and 1 July 2027 for the maximum life cycle carbon footprint thresholds.	Article 7	Annex II (Carbon Footprint)
7	Performance and durability of rechargeable industrial and EV batteries	Information requirements on performance and durability Minimum performance and durability requirements for industrial batteries as a condition for placement on the market	Article 10 Article 12 Article 14	Annex IV (performance) Annex V (Safety) Annex VII (SoH)
8	Non- rechargeable portable batteries	Technical parameters for performance and durability of portable primary batteries Phase out of portable primary batteries of general use	Article 9	Annex III
9	Recycled content in industrial, EV and automotive batteries	Mandatory declaration of levels of recycled content, in 2025 Mandatory levels of recycled content, in 2030 and 2035	Article 8 (material recovery on EV batteries)	
10	Extended producer responsibility	Clear specifications for extended producer responsibility obligations for industrial batteries Minimum standards for PROs	Article 17 Article 18 All Chapter	Annex VIII, Annex IX (Conformity)
11	Design requirements for portable batteries	Strengthened obligation on removability New obligation on replaceability	Article 11	
12	Provision of information	Provision of basic information (as labels, technical documentation or online) Provision of more specific information to end-users and economic operators (with selective access) Setting up an electronic information exchange system for batteries and a passport scheme (for industrial and electric vehicle batteries only)	Article 13 Article 64 Article 65 (battery passport)	Annex VI (Labelling) Annex XIII (European Electronic Exchange System)
13	Supply-chain due diligence for raw materials in industrial and EV batteries	Mandatory supply chain due diligence	Article 6, Article 71 Article 39	Annex I (Hazardous Substances) Annex X (List of

				raw materials and risk categories)

7. Conclusions and recommendations

7.1. Conclusions

Chapter 2

The market share of battery electric vehicles and plugin electric vehicles is growing substantially since 2018 and had in 2021 an average of 20% in EU 27. There is no standard battery in electric vehicles, the commonly used battery cells have different cathode compositions and types of formats. There are three main types of cell formats that battery manufactures provide: cylindrical, prismatic and pouch cells. When looking to lithium battery chemistries used in vehicles on the market there are three widely used compositions for the cathode, namely LFP, NMC and NCA batteries.

The design of the battery pack is unique to each car manufacturer based on several intrinsic characteristics of the battery cells, manufacturability, mechanical strength, available space, needed energy capacity and voltage level. Many car OEMs are partnering with several battery suppliers. The uniqueness of each battery pack and the variety of used battery formats and chemistries makes dismantling labour intensive and recycling routes challenging to maintain material quality.

Observing new cars on the market, a clear trend of increasing battery capacity is seen. On the one hand, customers demand larger driving ranges, on the other hand, battery production cost decreased significantly, explaining the growing battery capacity. Many electric vehicles on the market have a battery capacity exceeding 60kWh and a driving range of more than 300km.

Chapter 3

The batteries that are on the road are safe, battery technology is ready for e-mobility applications. However, with the increase of the battery demand, battery production and usage should become more sustainable. To achieve that goal, different alternatives are being now under research. The first possibility is the usage of novel technologies, such as solid state with promising properties such as higher energy densities. However, other technologies like Sodium-Ion or lithium- Sulphur are as well under research so to avoid the usage of critical materials. Another research action is to extend the cycle lifetime of the batteries we have now in place. For that, smart functionalities like sensor implementation or self-healing properties are now under research to be ready to implement. Additionally, an accurate diagnosis is key to use the battery as long as possible.

A proper diagnosis will enable the possibility of second life where failures and potentially detect the knee-point. There are many diagnosis tools for State-of-Health or Remaining-Useful-Life estimation, however the problem is that those algorithms are technology dependent and are not so easy to extrapolate. This means that a SoH algorithm developed for example for a specific NMC battery is not directly usable for a LFP battery. Manufacturing of batteries play a key role as well in terms of sustainability. To produce more homogeneous and equal batteries, which will enable a longer lifetime of the battery pack, digital tools such as digital twins and industry 4.0 are now beginning to be put in place in pilot lines or production lines when producing batteries. In relation to this, the battery passport, which is mentioned as a requirement in the new Battery Regulation, is a novel concept aiming to introduce standardized labels for each of the produced battery cells. This concept is now under development in an ongoing German funded project called “Battery Pass”.

Chapter 4

Besides, decreasing traffic by increased multi-modal mobility and public transport, an important contribution to a timely decarbonization of the transport sector needs to come from electrifying passenger cars. However, the production of batteries creates specific environmental impacts that is multiplied with an increasing battery capacity per vehicle. The first step in reducing the environmental impacts of batteries is to measure and understand where in the supply chain environmental impacts are originating.

To streamline the method to measure environmental footprints of batteries in the EU context, the European Commission has formulated a ‘Product Environmental Footprint Category Rules’ (PEFCRs) for rechargeable single cells or/and batteries used in electric vehicles. This is to date the general method on how to perform a Life Cycle based assessment of traction batteries in the European context.

The carbon footprint and energy consumption of lithium batteries is examined from a life cycle assessment approach considering the raw material acquisition, the production processes of the active materials and the battery pack components, the distribution and the end-of -life stage. The included battery chemistries are lithium iron phosphate (LFP), lithium titanate oxide (LTO), lithium cobalt oxide (LCO), lithium manganese oxide (LMO), nickel cobalt manganese (NCM), nickel cobalt manganese (NCM) and nickel cobalt aluminium (NCA). The currently most widely used chemistries for automotive applications are NMC and NCA.

The most significant contribution to the impact on climate change comes from manufacturing the battery cells itself. The manufacturing energy (especially electricity usage) and the production of the active materials of the cathode contributes the most to the greenhouse gases. The listed carbon footprints are from research project developing chemistries on lab scale, yielding higher values compared to optimised processes for mass production.

It is possible to reduce the carbon footprint of batteries significantly. High production capacity and an electricity mix with low carbon intensity are pertinent to further optimize and decrease the carbon footprint of battery manufacturing. A factor three reduction potential of the carbon footprint is achievable when optimization of energy losses during manufacturing and a higher battery pack energy density are assumed.

Today, there are significant supply chain risks linked to batteries needed in various industries in Europe. The production of the raw materials, the refining and the manufacturing of the active materials as well as the manufacturing of the battery cells are predominantly done outside Europe. The largest battery manufacturers are Asian.

The battery materials with the largest supply risks are lithium, cobalt, natural graphite, bauxite (for aluminium production) and niobium, silicon and titanium for future generations of batteries

To improve European resilience, the European Commission is drafting a pathway to ramp up (1) the mining and refining of domestic raw materials, (2) domestic production of batteries and (3) substitution and circularity of battery materials and components.

Chapter 5

After a useful life as a traction battery, different end-of-life possibilities emerge for lithium batteries. When proper diagnostics and safe disassembly procedures are in place, repairing a battery pack is a good strategy to prolong the useful life of the battery. To prolong the service life of traction batteries in cars new innovations including predictive maintenance and self-healing properties are considered. Battery packs (or parts) that are in good condition can be removed and reused in another vehicle. However, when the diagnosis of the battery indicates that the State-of-Health is too low for a mobility application several other options exist to recuperate parts of the value of the battery.

Batteries that contain enough remaining capacity and potential lifetime, can be repurposed in stationary applications to bring services to the transmission and distribution operators or to private customers. Various battery sizes can be examined for second-life applications. In some cases, where larger battery capacity is needed, the battery packs of electric vehicles are not dismantled but fully reused with their original casing, cooling system and battery management system. In other cases, the battery pack is dismantled at module level of cell level and tested before the new battery pack is composed and rebuilt. With more dismantling the labour cost increases, and the repurposed battery will need new customized components such as a casing, cooling circuit and battery management system, adding to the final cost of the second-life battery.

When reusing is not an option, the battery should follow a recycling process. Typical recycling processes are direct, hydrometallurgical and pyrometallurgical recycling. These three techniques affect the quality of material composition in different ways, making them suitable to recover material streams or mixtures that can enter the supply chain at different stages. Direct recycling doesn’t alter the material composition of the cathode, making it possible to recoat recovered active cathode material directly during the production process of a battery cell. Hydrometallurgy recovers material streams that can enter the production chain of active materials. Thanks to pyrometallurgy processes, basic metals such as cobalt and nickel can be recovered from waste streams. These metals can be used during the refining steps of the production chain. Hydrometallurgy can recover many more materials compared to pyrometallurgical recycling but needs more pre-treatment steps to generate the material streams that can be processed, it recovers aluminium, lithium, manganese and graphite. The diversity of battery packs developed and used among car manufacturers is large. To ensure safe and cost-effective recycling the batteries are sorted in their various chemistries, sizes and cell shapes. To safely handle batteries during the recycling processes it is important to discharge the battery cells fully to prevent explosions, fires, or leakages of toxic gasses.

To improve the quality of the materials entering the material extraction processes battery packs need to be dismantled. However, automotive battery packs are complex systems composed of various components: BMS, modules, cooling system, electronics for control, cables … This complexity presents obstacles during the dismantling of battery packs, favouring the adaptability of skilled labour over automatization. Depending on the subsequent recycling process the battery packs are dismantled into modules or cells. Battery modules can be directly recycled in pyrometallurgical processes, where plastic parts are even used as energy. Other methods such as direct recycling and hydrometallurgy need more dismantling and pre-treatment steps including a combination of thermal, mechanical, physical or chemical processes that create and concentrate material fractions before they enter the material extraction processes.

Circular economy is a transition towards a new economic paradigm that can be used to further enhance the societal benefits of electric vehicles by tapping into unused secondary material streams, by intensifying the services of resources and by retaining their intrinsic value in a closed Technosphere. Design for disassembly and circularity will become pertinent when designing the first life and the paradigm shift will need to be supported and streamlined with new regulation and legislation. All the elements of the new value network that emerges during this transition needs to be developed and optimized, including the reverse logistics, collection points, dismantling shops, refurbishment and new applications.

Chapter 6

It is important to understand the needed components of a battery and how a battery works to be aware of the possible risks and failures that can happen. Moreover, it is critical to select the best fitting cell design considering the used technology and final application as well as to keep always a proper BMS running the full battery pack. Several standards and regulations are in place to prevent any possible failure in the usage stage of the battery. They are mostly related to the abuse tests to be developed for Li ion battery based electric vehicles. Those tests for mechanical, electrical, environmental, and chemical abuse are described in the standards and regulations. It is important to highlight as well that as the battery technology evolves, the standards and regulations also change and modify therefore it is important to get updated and check the valid and current standards and regulations. This is the case of the Commission's EU Battery Regulation proposal, replacing the previous battery directive (2006/66/EC). The objective of the new regulation is to a) strengthen battery sustainability throughout their life cycle, by ensuring minimum sustainability requirements for batteries placed in the EU internal market, b) increase the resilience of the EU battery supply chain by closing the materials loop, c) reduce the environmental and social impacts throughout all the stages of the life cycle of batteries. Concretely, the new EU battery regulation proposes to include a battery passport, a carbon footprint declaration, increase the recycling and material recovery targets, increase the collection rate, define responsibilities, establish performance and durability, and set up several definitions. Each of these requirements will need to be in place at different dates.

7.2. Recommendations

Lithium batteries are crucial to electrify the transport sector and the energy transition. Demand for batteries is expected to grow substantially and the supply chain is at risk in the EU. To strengthen the EU position and to reduce the dependency on Asian battery market, the EU will diversify its materials supply and improving the domestic manufacturing capabilities for mining, refining and battery production.
Raw material substitution and circular automotive batteries play another important role. To strengthen the circularity of automotive batteries following is recommended:

1) ***Make propulsion battery accessible for authorised repairers, increase transparency of diagnostic information and make batteries repairable***

There is a **lack of open and complete information on the state of health of the batteries and their embedded materials**. This information is threated as confidential by the original manufacturers as it is deemed valuable. However, data transparency is key for circular management of batteries. Everyone in the reverse supply chain needs to receive correct historic data. Detailed, reliable and verifiable (by third parties) information on the battery during its life is needed for the consumer, technical control, predictive maintenance, refurbishment in second life and eventually the recycler to transform this industry to a circular approach in which various new innovative initiatives can enter the market. Remaining capacity (and historic data on the usage) is key for circularity and belongs to the user of the battery, not the OEM. **To support open and verifiable information a strong regulatory framework and a battery passport is crucial.**

2) Strengthen the regulatory framework

Uniform international procedures need to be set up on **End-of-life treatment of batteries** including the reverse logistics and the different options for recycling and repurposing batteries.

Standardized methods to allocate environmental impacts of different recycling and repurposing options will support unbiased views of the benefits circularity can have on the Product Environmental Footprint (PEF) of batteries.

To enable new actors to organize and innovate the repair of batteries and the second life, a **standardised and verifiable diagnosis** of state conditions (e.g., SoH diagnosis) is essential. To create a trustworthy level playing field for new after-sales actors, test procedures for third party diagnostics need to be defined as well as measurement points needs to be easily accessible in the car.

3) Set up a battery passport

Tracking materials and battery information across life cycle (whereabouts, conditions, eco-social performance). Obligations to report uniform and open data that is traceable and verifiable by independent third parties are essential. The data should include social and environmental aspects of the battery along its supply chain and should include information on the state condition and performance, while **maintaining privacy and security**. The data should help to verify compliance with human rights and environmental regulation and is referred to as the battery passport.

Data requirements needs to be listed per process and actor for the full value chain, including the recycling and repurposing steps.

To enable circular batteries transparent and verifiable data and diagnosis is needed of: State-of-Health, State-of-Charge, Voltage, temperature, depth of discharge and number of recorded incidents.

4) Create a reverse battery value chain

A reverse battery value chain is non-existing and needs to be established including all the different steps starting with the collection, testing and dismantling facilities, the repurposing workshops that manufacture second-life batteries, to the recycling processes and plants. The reverse battery value chain needs to be established on a European-wide level. To improve the efficiency of the overall process the network needs to be optimized considering, the location and sizes of different collection and dismantling facilities, the location of the logistic hubs, the scalability of the processes to accommodate market ramp up, the degree of automatization, the adaptability of the process to changing chemistry and cell types and the location and yield of the recycling infrastructure.

5) Design for circularity targets

Automotive battery packs are not yet designed to be easily dismantled by third parties and with a full circular value creation in mind that crosses the levels of the initial production company. Circularity is an optimization of material use in society beyond the scope of a single product of a single company and therefor needs collaboration on system level.
An industry-wide collaboration initiating a common approach to design for circularity and dismantling can set minimum requirements to standardize elements of design for circularity and initiate value creation throughout consecutive life cycles. The standards should be initiated by the full industrial ecosystem to foster the full synergetic potential of circularity, including not only the car manufacturers but as well the collecting and dismantling facilities, the refurbishment workshops, the machine builders and the recyclers.

6) The necessity of training, education and research

The full electrification of the vehicle fleet needs many skilled employees leading the pathway. This large transition affects many disciplines in various industrial sectors to rethink business models, re-engineer machining and tools, dismantle batteries and automate processes. Employees will need to receive the proper training to acquire new skill sets and the younger generation should receive education that teaches them how to confront the large transitions society needs to go through the next decades. Transitions are period of ample opportunities to create new innovations. To accelerate innovations,
Investments in R&D and open research infrastructure can foster the collaboration between industry, academia and civil society to effectively accelerate the transition towards a climate neutral the transport and power sector.

8. References

[1] European Alternative Fuels observatory. Online available on: https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27. European Commission 2022

[2] Brudermüller M., Sobotka B., Waughray D. A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation, World Economic Forum 2019

[3] Choi, J.W.; Aurbach, D. Promise and reality of post-lithium-ion batteries with high energy densities. Nature Reviews Materials 2016, 1.

[4] European Electric Vehicle cell supply chain, CIC Energigune

[5] Schmuch, R.; Wagner, R.; Hö̈rpel, G.; Placke, T.; Winter, M. Performance and cost of materials for lithium-based rechargeable automotive batteries. Nature Energy 2018

[6] Morse I, A dead battery dilemma. Science Vol 372, Issue 654 pp. 780-783. 2021.

[7] Harper G., Sommerville R., Kendrick E., Driscoll L., Slater P., Stolkin R., Walton A., Christensen P., Heidrich O., Lambert S., Abbott A., Ryder K., Gaines L., Anderson P. Recycling lithium-ion batteries from electric vehicles.Nature 2019.

[8] EMIRI Roadmap

[9] Z. Huang, L. Tang, and L. Su, “The design of data acquisition system based on fpga and usb2. 0 for bms of electric vehicle,” in 2011 International Conference on Electrical and Control Engineering, pp. 1334–1337. IEEE, 2011.

[10] C. Truchot, M. Dubarry, and B. Y. Liaw, “State-of-charge estimation and uncertainty for lithium-ion battery strings,” Applied Energy, vol. 119, pp. 218–227, 2014.

[11] K. S. Ng, C.-S. Moo, Y.-P. Chen, and Y.-C. Hsieh, “Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries,” Applied energy, vol. 86, no. 9, pp. 1506–1511, 2009.

[12] O. Barbarisi, F. Vasca, and L. Glielmo, “State of charge kalman filter estimator for automotive batteries,” Control Engineering Practice, vol. 14, no. 3, pp. 267–275, 2006.

[13] https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs

[14] M. S. Hosen, D. Karimi, T. Kalogiannis, A. Pirooz, J. Jaguemont, M. Berecibar, and J. Van Mierlo, “Electro-aging model development of nickel-manganese-cobalt lithium-ion technology validated with light and heavy-duty real-life profiles,” Journal of Energy Storage, vol. 28, p. 101265, 2020.

[15] Machine-learning techniques used to accurately predict battery life. Berecibar, M. 325-326, s.l.: Nature, 2019, Vol. 568.

[16] Critical review of state of health estimation methods of Li-ion batteries for real applications. M. Berecibar, I. Gandiaga, I. Villarreal, N. Omar, J. Van Mierlo, P. Van den Bossche. s.l.: Renewable and Sustainable Energy Reviews 56, 2016, Vol. 56.

[17] https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs

[18] C. A. Ooi, D. Rogers, and N. Jenkins, “Balancing control for grid-scale battery energy storage system,” Proceedings of the Institution of Civil Engineers-Energy, vol. 168, no. 2, pp. 145–157, 2015.

[19] J. Qi and D. D.-C. Lu, “Review of battery cell balancing techniques,” in 2014 Australasian Universities Power Engineering Conference (AUPEC), pp. 1–6. IEEE, 2014.

[20] M. Daowd, N. Omar, P. Van Den Bossche, and J. Van Mierlo, “Passive and active battery balancing comparison based on matlab simulation,” in 2011 IEEE Vehicle Power and Propulsion Conference, pp. 1–7. IEEE, 2011.

[21] K. Vitols, “Design of an embedded battery management system with passive balancing,” in 2014 6th European Embedded Design in Education and Research Conference (EDERC), pp. 142–146. IEEE, 2014.

[22] Z. B. Omariba, L. Zhang, and D. Sun, “Review of battery cell balancing methodologies for optimizing battery pack performance in electric vehicles,” IEEE Access, vol. 7, pp. 129 335–129 352, 2019.

[23] J. Lin, X. Liu, S. Li, C. Zhang, and S. Yang, “A review on recent progress, challenges and perspective of battery thermal management system,” International Journal of Heat and Mass Transfer, vol. 167, p. 120834, 2021.

[24] A. R. Baird, E. J. Archibald, K. C. Marr, and O. A. Ezekoye, “Explosion hazards from lithium-ion battery vent gas,” Journal of Power Sources, vol. 446, p. 227257, 2020.

[25] “ISO 26262: Road vehicles — Functional safety,” International Organization for Standardization, Geneva, CH, Standard, 2018.

[26] H. Rahimi-Eichi, U. Ojha, F. Baronti, and M.-Y. Chow, “Battery management system: An overview of its application in the smart grid and electric vehicles,” IEEE Industrial Electronics Magazine, vol. 7, no. 2, pp. 4–16, 2013.

[27] Y. Kang, B. Duan, Z. Zhou, Y. Shang, and C. Zhang, “A multi-fault diagnostic method based on an interleaved voltage measurement topology for series connected battery packs,” Journal of Power Sources, vol. 417, pp. 132–144, 2019.

[28] M.-K. Tran and M. Fowler, “A review of lithium-ion battery fault diagnostic algorithms: Current progress and future challenges,” Algorithms, vol. 13, no. 3, p. 62, 2020.

[29] B. Xia, C. Mi, Z. Chen, and B. Robert, “Multiple cell lithium-ion battery system electric fault online diagnostics,” in 2015 IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1–7. IEEE, 2015.

[30] L. Maharjan, T. Yamagishi, H. Akagi, and J. Asakura, “Fault-tolerant operation of a battery-energy-storage system based on a multilevel cascade pwm converter with star configuration,” IEEE Transactions on Power Electronics, vol. 25, no. 9, pp. 2386–2396, 2010.

[31] S. Divyashree, P. Madhavan, and A. Ranjeev, “Battery management system integrated with can bus safety control environment for electric vehicle,” International Journal Of Engineering Research & Technology (IJERT), vol. 9, no. 9, 2020.

[32] Birkl, C.; Roberts, M.; McTurk, E.; Bruce, P.; Howey, D. Degradation diagnostics for lithium ion cells. Journal of Power Sources 2017, 341, 373–386.

[33] Dubarry, M.; Truchot, C.; Liaw, B.Y. Synthesize battery degradation modes via a diagnostic and prognostic model. Journal of Power Sources 2012, 219, 204–216.

[34] Keil, P.; Jossen, A. Calendar Aging of NCA Lithium-Ion Batteries Investigated by Differential Voltage Analysis and Coulomb Tracking. Journal of The Electrochemical Society 2017, 164, A6066–A6074.

[35] Broussely, M.; Herreyre, S.; Biensan, P.; Kasztejna, P.; Nechev, K.; Staniewicz, R. Aging mechanism in Li ion cells and calendar life predictions. Journal of Power Sources 2001, 97-98, 13–21.

[36] Hoog, J.D.; Timmermans, J.m.; Ioan-stroe, D.; Swierczynski, M.; Jaguemont, J.; Goutam, S.; Omar, N.; Mierlo, J.V.; Bossche, P.V.D. Combined cycling and calendar capacity fade modeling of a Nickel- Manganese-Cobalt Oxide Cell with real-life profile validation. Applied Energy 2017, 200, 47–61.

[37] Jaguemont, J.; Boulon, L.; Dub́e, Y. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. Applied Energy 2016, 164, 99–114.

[38] Burns, J.; Stevens, D.; Dahn, J. In-Situ Detection of Lithium Plating Using High Precision Coulometry. Journal of the Electrochemical Society 2015, 162, A959–A964.

[39] Zheng, H.; Sun, Q.; Liu, G.; Song, X.; Battaglia, V. Correlation between dissolution behavior and electrochemical cycling performance for LiNi1/3Co1/3Mn1/3O2-based cells. Journal of Power Sources 2012, 207, 134–140.

[40] Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M. A review on the key issues for lithium-ion battery management in electric vehicles. Journal of Power Sources 2013, 226, 272–288.

[41] Berecibar, M.; Gandiaga, I.; Villarreal, I.; Omar, N.; Van Mierlo, J.; Van den Bossche, P. Critical review of state of health estimation methods of Li-ion batteries for real applications. Renewable and Sustainable Energy Reviews 2015, 56, 572–587.

[42] Hosen, M.; Karimi, D.; Kalogiannis, T.; Pirooz, A.; Jaguemont, J.; Berecibar, M.; Van Mierlo, J. Electro-aging model development of nickel-manganese-cobalt lithium-ion technology validated with light and heavy-duty real-life profiles. The Journal of Energy Storage 2020, 28.

[43] Li, Y.; Zou, C.; Berecibar, M.; Nanini-Maury, E.; Chan, J.; Van den Bossche, P.; Van Mierlo, J.; Omar, N. Random forest regression for online capacity estimation of lithium-ion batteries. Applied Energy 2018, 232, 197–210.

[44] Battery2030+ Roadmap, March 2020

[45] https://cordis.europa.eu/project/id/957221

[46] https://cordis.europa.eu/project/id/955930

[47] https://cordis.europa.eu/project/id/957273

[48] https://cordis.europa.eu/project/id/957225

[49] https://cordis.europa.eu/project/id/957202

[50] Y. Cheng, et al. Development and application of self-healing materials in smart batteries and supercapacitors, Chemical Engineering Journal 380 (2020) 1225652

[51] Advanced Materials for Clean and Sustainable Energy and Mobility, EMIRI key R&I priorities, Emiri, September 201

[52] Battery2030+ Roadmap, March 2020

[53] ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Frameworks. 2006.

[54] European Platform on Life Cycle Assessment. Online Available on: https://eplca.jrc.ec.europa.eu/. European Commission.

[55] Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. Online available on: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279. 2021

[56] Siret C., Tytgat J., Ebert T., Mistry M., Thirlaway C., Schutz B., Xhantopoulos D., Wiaux J., Chanson C., Tomboy W., Pettit C., Gediga J., Bonell M., Carrillo V. PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications. Online available on: https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf. 2020

[57] Peters, J., Baumann, M., Zimmermann, B., Braun, J., Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews 67, p. 491-506, 2017

[58] Philippot M., Alvarez G., Ayerbe E., Van Mierlo J., Messagie M. Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs. Batteries 2019

[59] US Energy Information Administration. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018. Available online: http://www.eia.gov/outlooks/aeo/ assumptions. 2018.

[60] Philippot M., Smekens J., Van Mierlo J., Messagie M. Life cycle assessment of silicon alloy based lithium-ion battery for electric vehicles. Urban Transport XXIV. WIT Press, 2019.

[61] Diekmann, J., Hanisch, C., Froböse, L., Schälicke, G., Loellhoeffel, T., Fölster, A.-S., Kwade, A. Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes. Journal of the Electrochemical Society 164, A6184–A6191. 2017

[62] European Commission. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Online available on: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474. 2020.

[63] Joint Research Center. Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020", doi: 10.2873/58081

[64] Mossali E., Picone N., Gentilini L., Rodrìguez O., Manuel J., Colledani M. Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments. Journal of Environmental Management 264. 2020.

[65] European Commission. Progress on competitiveness of clean energy technologies 6 & 7 - Batteries and Hydrogen Electrolysers. Online available on/ https://ec.europa.eu/energy/sites/default/files/documents/swd2021_307_en_autre_document_travail_service_part4_v2.pdf. 2021.

[66] Reddy T. Linden's handbook of batteries, 4th edition. New York, NY: McGraw- Hill, Inc.; 2011.

[67] Balducci A, Jeong SS, Kim GT, Passerini S, Winter M, Schmuck M, et al. Development of safe, green and high performance ionic liquids-based batteries (ILLIBATT project). J Power Sources 2011;196:9719–30.

[68] Kerner M, Lim D-H, Jeschke S, Rydholm T, Ahn J-H, Scheers J. Towards more thermally stable Li-ion battery electrolytes with salts and solvents sharing nitrile functionality. J Power Sources 2016;332:204–12.

[69] Janek J, Zeier WG. A solid future for battery development. Nat Energy 2016;1:16141.

[70] Yamamoto H, Mori H. Chapter 7: SBR binder (for negative electrode) and ACM binder (for positive electrode). In: Yoshio Masaki, Brodd Ralph J, Kozawa A, editors. Lithium-ion batteries science and technologies. New York: Springer; 2009.

[71] Reddy T. Linden's handbook of batteries, 4th edition. New York, NY: McGraw- Hill, Inc.; 2011.

[72] Jacoby M. Burning batteries, chemical & engineering news. C & EN Chem Eng News 2007;85:26–8.

[73] Balakrishnan PG, Ramesh R, Prem Kumar T. Safety mechanisms in lithium-ion batteries. J Power Sources 2006;155:401–14.

[74] Mikolajczak C, Kahn M, White K, Long RT. Lithium-ion batteries hazard and use assessment. In: Exponent failure analysis associates IFPRF, editor. Exponent Failure Analysis Associates, Inc., Fire Protection Research Foundation; 2011.

[75] Yeow K, Teng H, Thelliez M, Tan E. 3D thermal analysis of Li-ion battery cells with various geometries and cooling conditions using abaqus. In: Proceedings of the SIMULIA community conference; 2012, p. 1–16.

[76] Levy SC, Bro P. Battery hazards and accident prevention. New York and London: Plenum Press; 1994.

[77] Lamb J, Orendorff CJ. Evaluation of mechanical abuse techniques in lithium ion batteries. J Power Sources 2014;247:189–96.

[78] https://www.sae.org/standards/content/j2464_202108

[79] https://www.sae.org/standards/content/j2929_201302/

[80] https://www.iso.org/standard/68665.html

[81] Euro NCAP bulletin on testing vehicles with electrified propulsions

[82] Ashtiani CN. Analysis of battery safety and hazards' risk mitigation. 19th ed. Washington, DC; 2008, p. 1–11.

[83] Doughty DH, Crafts CC. SAND 2005–3123: freeDomCAR electrical energy storage systems abuse test manual for electric and hybrid electric vehicle applications; 2005.

[84] https://op.europa.eu/en/publication-detail/-/publication/fd8e6b47-d767-11e4-9de8-01aa75ed71a1

[85] https://unece.org/transport/vehicle-regulations-wp29/standards/addenda-1958-agreement-regulations-21-40.

[86] A. Lecocq, M. Bertana, B.Truchot, Marlair G. Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle International Conference on Fires In Vehicles - FIVE 2012. Chicago, United States2012. p. 183-94.

[87] Andersson P, Blomqvist P, Lorén A, Larsson F. Investigation of fire emissions from Li-ion batteries. SP technical research institute of Sweden2013.

[88] Sturk D., Hoffmann L., A. AT. Fire Tests on E-vehicle Battery Cells and Packs. Traffic Inj Prev. 2015;16:159-64.

[89] https://unece.org/transport/documents/2022/04/standards/un-gtr-no22-vehicle-battery-durability-electrified-vehicles

[90] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798