LIB TECHNOLOGY MAPPING REPORT

A BATMAN report on current and future trends within lithium-ion battery chemistry

Preface

The BATMAN project started in 2019 and is being managed by the Eyde Cluster. The project name reflects the management of batteries; *Lithium ion BATteries - Norwegian opportunities within sustainable end-of-life MANagement, reuse and new material streams*. The expected increase of electro-mobility and transition to renewable energy will lead to an exponential growth of lithium-ion battery demands and as a result the use of relevant raw materials. This represents a huge opportunity for Norwegian businesses as Norway is a first mover within the electric mobility sphere and means that Norway will be one of the first countries that will have to handle large amounts of used lithium-ion batteries.

This report is one of the main deliverables in work package 1; Technology Mapping. This work package is led by Institute for Energy Technology (IFE). In milestone 1.1 of this work package, a technology mapping of current and future lithium-ion battery (LIB) chemistries is promised. This will ensure that the battery material flow analysis can give valuable forecasts and insights built on strong data. The report consists of a description of state-of-the art technology within the lithium-ion battery chain, following a more detailed description within the different transportation segments. This report will be updated with new data and possibly additional segments in 2021.

The information presented in this report is based on literature studies as well as experience and know-how within IFE from past and ongoing projects in the field of lithium-ion batteries. As the field of LIBs is constantly changing, and the demand of future LIB capacity is expected to increase exponentially to the year 2030, the numbers and facts in this report will soon be somewhat outdated. Thus, there is a need for the updated report in 2021 to have a closer look at what will have changed in the two-year period and to verify the bigger trends outlined here.

Kjeller, December 2019

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Introduction

The report is built to introduce the reader to Li-ion battery (LIB) needs based on raw materials, available chemistries, recent market reports and predictions.

We will start with an introduction to the raw materials that go into the LIB chain. This includes an overview on available resources (world-wide and within Europe), the current and estimated future demands, as well as associated issues.

Subsequently, a basic introduction on the principles of the LIB will be provided, including a description of its main constituents: the anode, the cathode and the electrolyte, but also other parts that go into the battery cells, modules and packs (such as current collectors, separators, binders, solvents, battery management system). We will elucidate what the individual raw materials introduced in the previous section are used for, describe the state-of-the-art chemistries and give a brief overview on their respective advantages and disadvantages. Insights into current developments of new and improved materials will be given, followed by an outlook and tentative predictions for future and new-generation LIBs and related technologies. At the end of this section, and overview on existing LIB factories and plans for new factories, focusing mainly on Europe, will be given.

As a next step, we will look at the LIB needs of different transport segments and introduce, which technologies/chemistries are currently being used and predicted to be used in the near future. We will give insights on estimated growth and demand scenarios as well as changes and developments in cell chemistries that are expected to influence future material needs. The focus of this section will be the sector of personal electric vehicles (including battery BEV, hybrid HEV and plug-in hybrid PHEV vehicles) and public transport vehicles. A brief overview on battery use and predictions for heavy duty vehicles, the maritime sector and stationary energy storage units will also be presented.

The last section will focus on reuse and recycling of LIBs. We will describe challenges and opportunities within these processes and give insights into current efforts.

As a starting point for more detailed information, especially regarding raw materials and battery technologies, a list of literature recommendations can be found in the appendix.

Definitions and abbreviations

Battery	If used on its own, it will always refer to a Li-ion battery
BEV	Battery Electric Vehicle
BMS	Battery Management System
CRM	Critical Raw Material
EoL	End-of-Life
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
LCE	Lithium Carbonate Equivalent
LCO	Lithium Cobalt Oxide cathode
LFP	Lithium Iron Phosphate cathode
LIB	Lithium-ion battery
LMO	Lithium Manganese Oxide cathode
LTO	Lithium Titanate anode
NCA	Nickel Cobalt Aluminium cathode
NMC	Nickel Manganese Cobalt cathode
PHEV	Plug-in Hybrid Electric Vehicle
PV	Personal Vehicle
Second life	If battery from EV is used in different application after use in EV
SEI	Solid electrolyte interphase
SOC	State of Charge
SoH	State-of-Health
SSB	Solid State Battery
xEV	An Electric Vehicle (either hybrid, plug-in hybrid or 100% electric)

1. Li-ion raw materials

In the upcoming section a short review on the status of raw materials going into the LIB chain is presented, where values relevant to Norway will be the focus. In some instances where these were not available, values relevant to Nordic countries (Norway, Finland, Sweden and Denmark), Europe and the EU will be used.

Firstly, some general information on the availability of the raw materials on a global scale: Figure 1 shows the abundance of elements as a fraction of the earth's crust as well as their price in USD/lb.

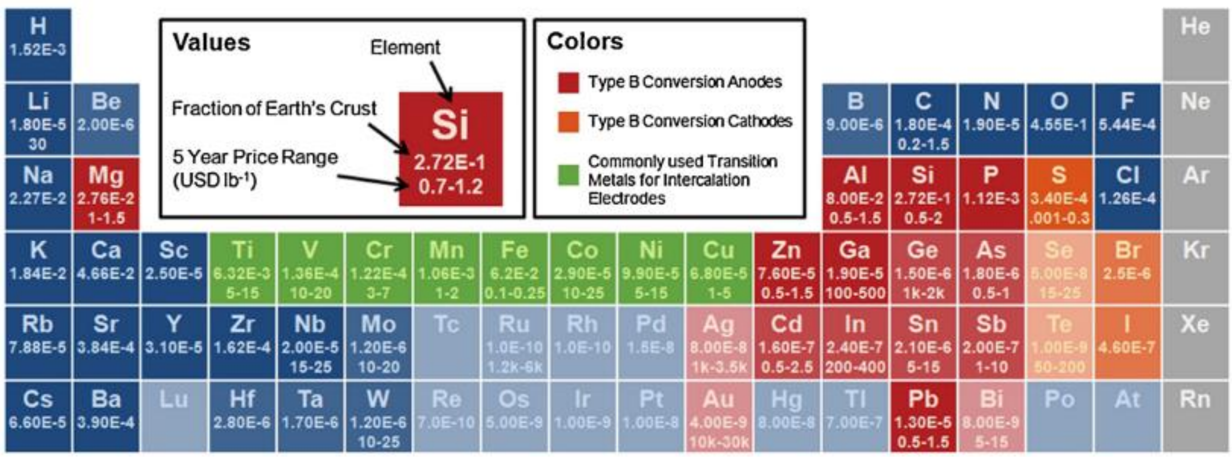


Figure 1: Availability of elements that may host Li as electrodes. Those faded have fraction below 10^{-5}. Carbon is an intercalation material, which is not defined in the color definition of this figure. [1].

The materials relevant for Li-ion battery production today are expanded upon further in the following sections, and include Lithium (Li), Carbon (C), Cobalt (Co), Nickel (Ni), Manganese (Mn), Copper (Cu), Aluminum (Al) and Silicon (Si). Most of the information on the raw materials input is taken from a report from 2017 by the Joint Research Center of EU unless otherwise noted [2]. For more information regarding raw materials for battery applications in the EU, a working document from the European Commission can be found in Appendix A1: Recommended literature [3].

Figure 2 illustrates an example of an estimated content of raw materials in an average battery pack for a light commercial EV. The materials used in this NMC based battery represent the typical distribution of elements within a LIB pack.

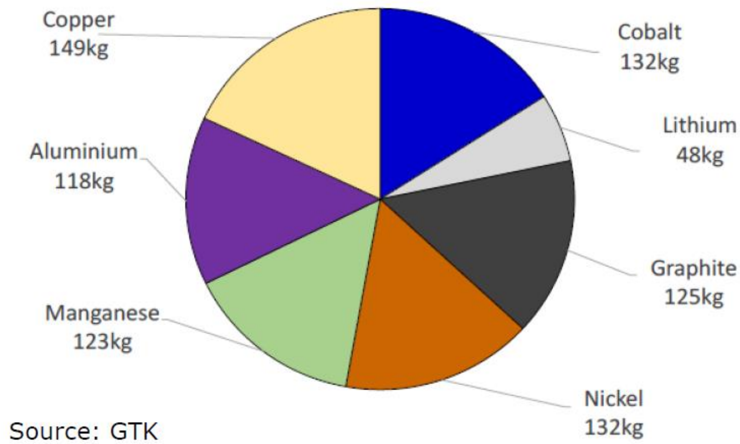


Figure 2: Estimated content of raw materials for a light commercial EV (based on a 300 kWh EV battery pack – NMC442) [4].

1.1. Lithium

Lithium (Li) is the lightest of all metals and the key-element of the Li-ion battery. Positive lithium ions shuttle between the two electrodes of the battery, corresponding to charge or discharge of the battery. There is a high average abundance of Li in the earth's crust (17 ppm) [5], with the main reserves located in South America (Chile, Argentina), China and Australia. Although Li is currently not listed as a critical raw material (CRM) in the EU, the EU is largely dependent on the import of Li for battery purposes.

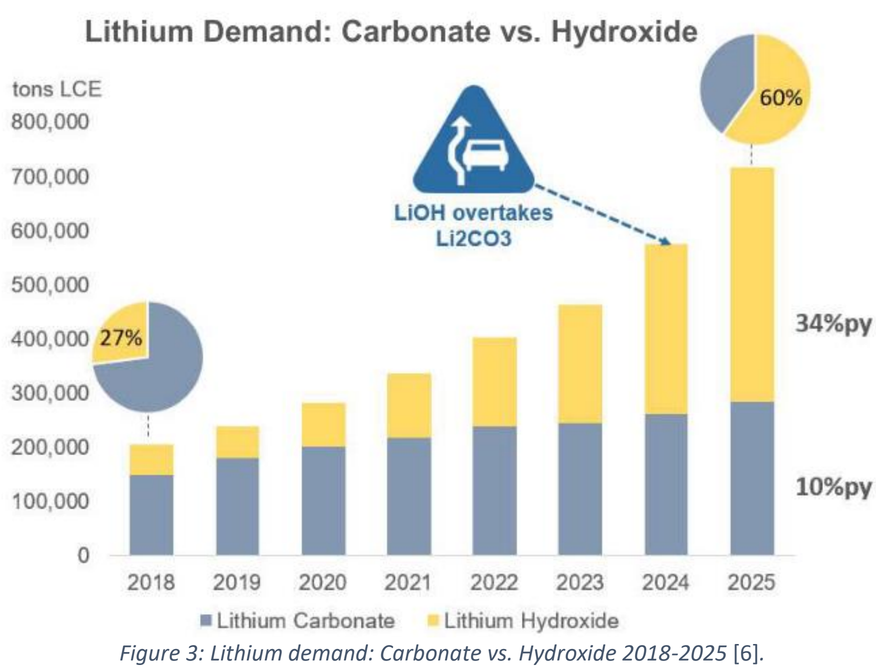


Figure 3: Lithium demand: Carbonate vs. Hydroxide 2018-2025 [6].

Lithium can be mined as both lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH). Historically, lithium carbonate has been used in batteries due to price and availability (used in LCO, NMC-111 and LMO, more information on these chemistries in Section 2.2). However, as the trend goes towards cathode materials with higher Ni contents (e.g. NCA, NMC-622, NMC-811), there is an increase in LiOH demands: LiOH is the preferred precursor[1] for the preparation of these materials. Most new mines and production capacity are targeting LiOH output, representing 75% of new/expanded capacity, and can be seen in Figure 3 [7][6].

The global supply market was around 229,000 tons of Lithium Carbonate Equivalent (LCE)[2] in 2018 (see Figure 9), mainly coming from Australia, Chile, Argentina and China. Efforts to reduce the European dependence on lithium import are ongoing: The Finish mining company Keliber plans to start Li excavation by the end of 2021 (expected 11,000 tons LCE/year) [8], the Wolfsberg Lithium Project in Austria announced their start of construction for LiOH[3] mining (10,000 tons/year) for 2019 [9], and Europe's largest lithium project Cinovec in the Czech Republic was announced to be up and running by mid-2022 (estimated reserves 7 million tons LCE, production 22,500 tons/year) [10]. Another European Li-project, Infinity Lithium Corporation in Spain, plans to start production of LiOH in Q2 2022 (estimated reserves 1.6 Mt LCE, production 15,000 tons/year) [6]. Further reserves are located in France, Portugal and Ireland [11]. 40% of the global Lithium supply was demanded for battery applications in 2015, and this share is expected to rise to 70% by 2025 according to Deutsche Bank analysis [11]. In 2015, the share used in EV battery packs was 14%, and is expected increase to 38% by 2025 (forecasts by Deutsche Bank, see **Error! Reference source not found.**).

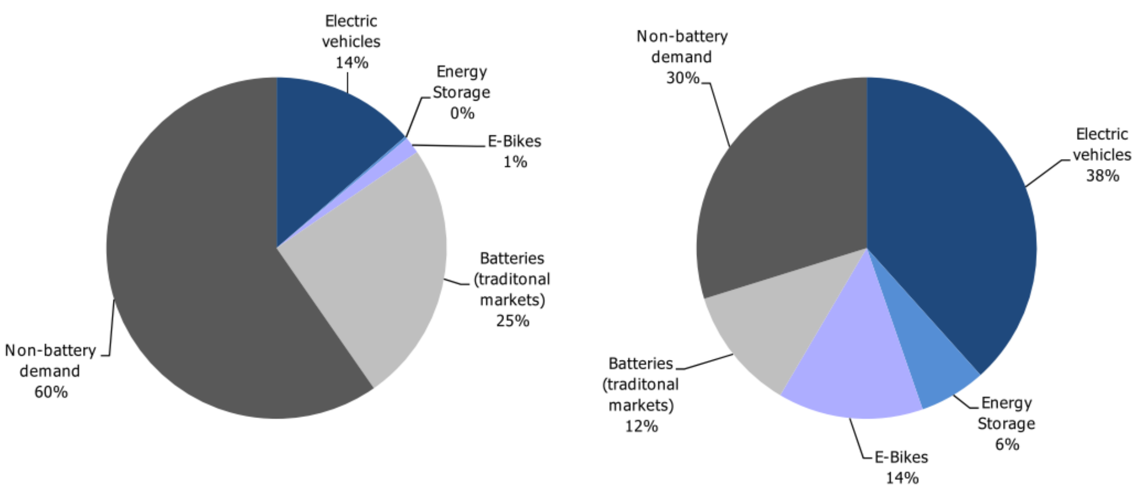


Figure 4: 2015 and 2025 lithium demand by application. Forecast by Deutsche Bank [11].

Analysis by Deutsche Bank AG/Sydney also estimates a flat and conservative assumption of 0.7 kg LCE/kWh of the battery. Projections show 200,000 tons LCE will be needed in 2025 for electric vehicles alone. This equates to the total current LCE supply in 2025, and justifies the need for recycling [11]. Currently, recycling is feasible but not economically viable according to [12].

[1] Precursor: A substance from which another is formed. Here used to describe how both Li_2CO_3 and LiOH can be used as precursor to the Li in a cathode material.
[2] 1 kg LCE = 0.1895 kg Li
[3] Lithium hydroxide. Required raw material for high Ni cathode materials according to reports [7] [6].

1.2. Carbon

Carbon (C) is the dominant anode material on the market today and is mostly used in its graphitic form to intercalate Li-ions. Natural graphite (NG) is listed as Critical Raw Material (CRM) as of 2017 [13]. Battery use has a share of NG of 10% [3], but is expected to increase at 19% CAGR [14]. Reserves are estimated at 230 trillion tons and in 2015 production was estimated at 1.2 million tons [2]. Production is concentrated in China covering 66% of share, with India (14%) and Brazil (7%) following. 57% of NG coming into the EU is from China, followed by Brazil (15%) and Norway[1] (9%). NG has high substitutability[2] in batteries with an index of 0.3. Recycling is at 0% today, and there is a forecasted surplus for natural graphite of 10% in 2020 [2].

In 2015, 91% of the anode market (total 75,000 tons) was covered by graphite, where artificial graphite (AG) has about 42 % of the market (by weight) and NG 49 % [2].While NG is made from mined graphite flakes, AG is made from heat treatment of coal tar or petroleum coke (by-products from the petroleum industry). Due to the higher cost (and higher purity) of production of AG, the target customer is usually highly specialized industry willing to pay a bit extra for a more stable product (like the solar energy storage industry, arc furnaces and high-end EVs), and therefore AG targets a different market than NG.

1.3. Cobalt

Cobalt (Co) is used in the cathode of the battery, where cobalt precursors such as cobalt sulphate or dihydroxide, are transformed into lithiated cobalt oxides ($LiCoO_2$) for chemistries used in lithium-ion batteries. Cobalt materials imported into Europe include refined cobalt metal, cobalt concentrate, and cobalt complex intermediates. Cobalt is listed as a Critical Raw Material (CRM) based on world resources (mainly in the Democratic Republic of Congo) and its economic importance to the EU [13]. Current global estimates are that 53% of all Co mined is being used in batteries. The cobalt consumption with regards to its application is shown in Figure 5 [15].

World-wide Co production in 2017 was 127 kt, which mainly (55%) originates from mined production in Congo; and the majority of refined global Co (46%) is produced in China [16]. The Co imported into the EU is mainly refined in Finland, and there is also some production of Co in Norway at Glencore Nikkelverk[3]. Co has low substitutability in batteries and has been assigned an index of 0.8. Long term projections for 2030 and 2050 show that demand of Cobalt could exceed supply even considering that higher recycling rates are expected in future [16][17]. Demand for use in batteries is expected to increase by factor of 4 in 2030 vs. 2019 as seen in Figure 9, mostly due to the popularity of Nickel-Manganese-Cobalt (NMC) cathodes [17]. However, it is unlikely that NMC-cathodes with high Co-contents will stay as main cathode after

[1] Skaland Graphite AS in Senja, sold to Australian company MRC LTD in spring 2019 [147]. Produces 12 000 t/year crystalline flake graphite.

[2] Substitutability index' is a measure of the difficulty in substituting the material, scored and weighted across all applications. Values are between 0 and 1, with 1 being the least substitutable.

[3] Glencore Nikkelverk in Kristiansand has an annual production of 5,200 t Co.

2030 due to research on low-Co (e.g. NMC-811) and Co-free chemistries. More on these cathode materials is presented in Section 2.2.3.

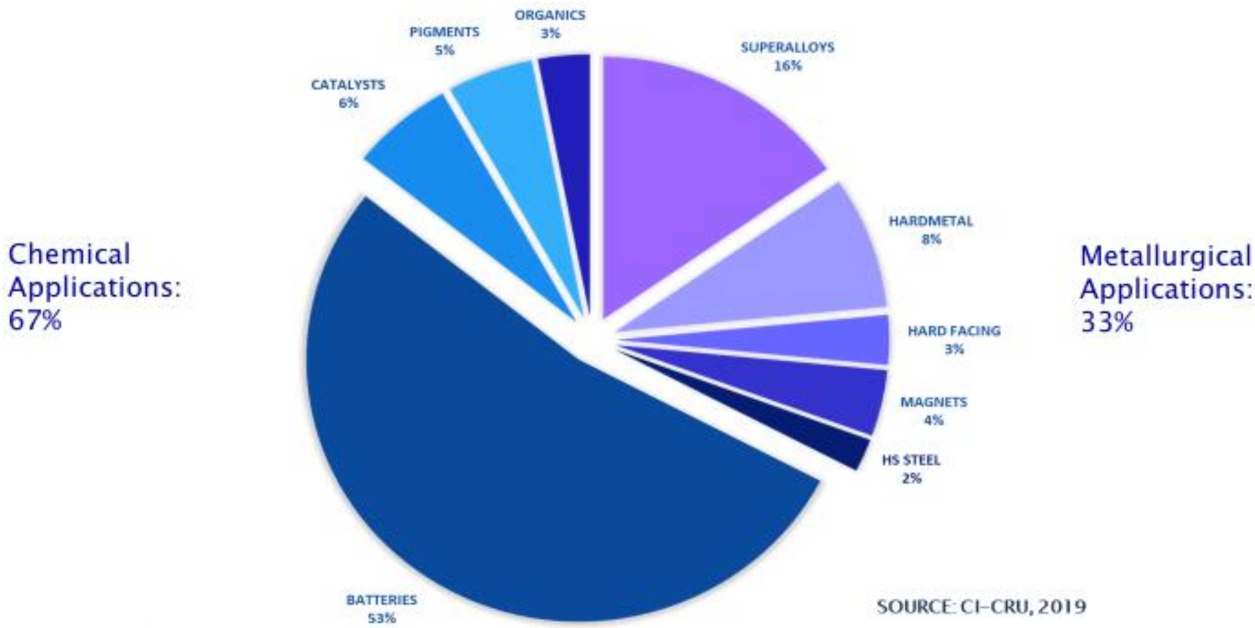


Figure 5: Cobalt consumption by end use 2018. Source: Cobalt Institute [15]

1.4. Nickel

Nickel (Ni) is used in the cathode of the battery, and as a raw material it enters the market in different forms: Class-1 Ni describes different forms of refined Ni (e.g. briquettes, powders) with a metal content of at least 99%, and is the basis for different Ni chemistries used in the Li-ion battery cathode. Other Ni products with a Ni content below 99% are commonly described at Class-2 Ni (e.g. ferronickel or nickel pig iron). In 2018, the total nickel mine production was 2.3 million tons, of which 46% was class-1 and 54% class-2.[1] Glencore Nikkelverk in Kristiansand refines Ni being mined in Canada and has an annual production of 92,000 t Ni making it the largest Ni-provider in Europe with 5% of the global Ni output.

Today around 70% of Ni products are used in stainless steel production, but there is a growing demand for high purity class-1 Ni in batteries as cathode chemistries are moving towards higher Ni-contents (e.g. in Nickel Manganese Cobalt-cathodes).[2] There is a projected increase of global need for class-1 Ni by a factor of 24 compared to 2018 values in 2030, as seen in Figure 9 [17]. In total, only 5% global nickel production is going into batteries [18].

Ni has historically played a large role in other battery types (e.g. nickel cadmium, NiCd and nickel metal hydride, NiMH) for small portable devices such as cordless power tools, but is now seeing

[1] Source: International Nickel Study Group
[2] Source: Roskill 2019 end use report via. Nickel Institute

an increasing interest as a large component in cathode chemistries for Li-ion batteries such as Nickel Cobalt Aluminum (NCA, 80% Ni content in the cathode) and different NMC chemistries (NMC111, 33% Ni as well as higher Ni-content = NMC532 50% Ni, NMC622 60% Ni and NMC811, 80% Ni) as we can see in Figure 6 [19]. NiMH batteries are still in use today, mostly in PHEV (see Section 3.1).

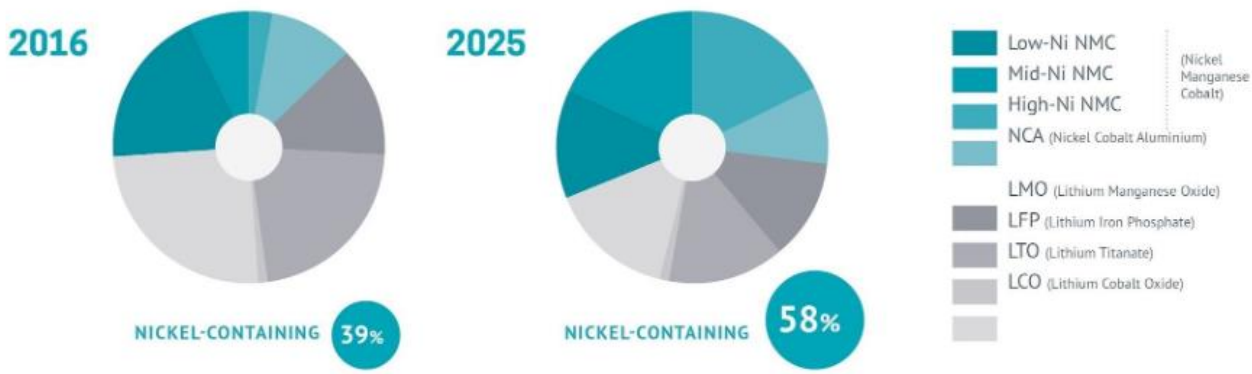


Figure 6: Increasing nickel-use in EV batteries [19].

1.5. Manganese

Manganese (Mn) is also used in the cathode of the battery, but at such low amounts (2% of global Mn production is used in batteries [3]) that even with the growth of NMC-cathodes the battery-share (compared to the steel-sector) is not expected to be large enough to have any effect on prices or supply. The projected increase in need is only 1.2 times compared to 2018, as shown in Figure 9 [17]. Manganese concentration in the earth's crust is high, and resources are assumed to be quite extensive.

1.6. Copper

Copper (Cu) is used as the current collector on the anode side of the battery, as well as being a part of the charging infrastructure wiring and going into the production of EVs. According to The International Copper Association its use in EV will drive an increase in the Cu-demand, growing from around 185,000 tons in 2017 to as much as 1.74 million tons in 2027, as shown in Figure 7 below. The study conducted by IDTechEx also estimates that 1.1-1.2 kg of Cu is needed per kWh of Li-ion battery, while charging stations require 0.7/8 kg Cu for a 3.3/200kW charger [20].[1]

Figure 7 also shows the future Cu need split into different segments which will be elaborated on in Section 3.

[1] There is approximately 25 kg of Cu in an average conventional vehicle. Source: https://copper-recycle.com/

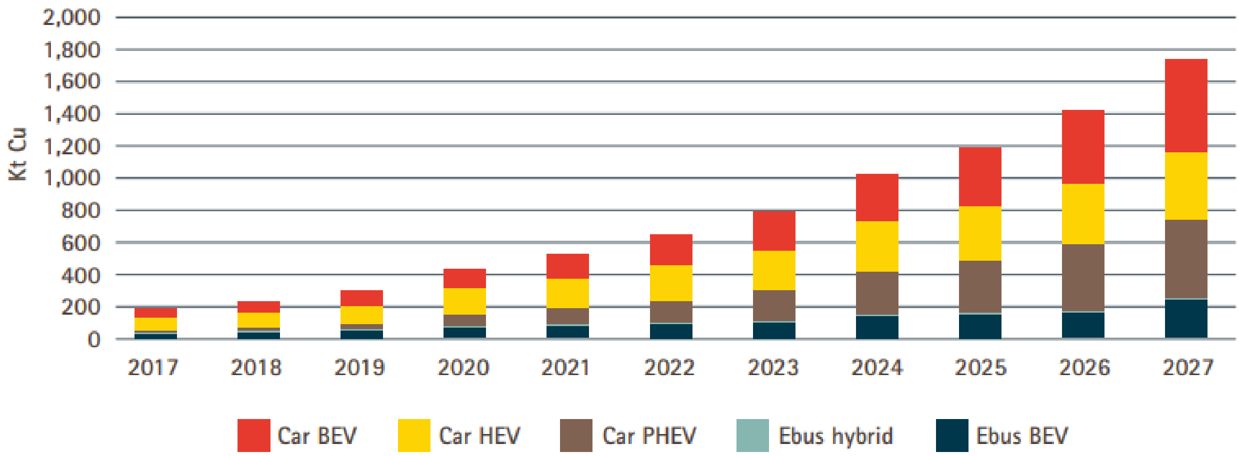


Figure 7: Electric vehicle Cu demand split into segments [20].

1.7. Aluminium

Aluminium (Al) is used as the current collector on the cathode side of the battery, but also in the NCA cathode (Nickel Cobalt Aluminium) used by Tesla (5% Al by weight according to [21]). Just like Cu, Al also plays a large role in the car itself as the battery cell and pack enclosures and will be needed as housing material for EV charging stations. This leads to a higher need for Al outside of the battery itself [21]. The total world resources are estimated to be between 55 and 75 million tons largely centered around China. Al production in Norway at Hydro is at 1.25 million tons[1] as seen in Figure 8.

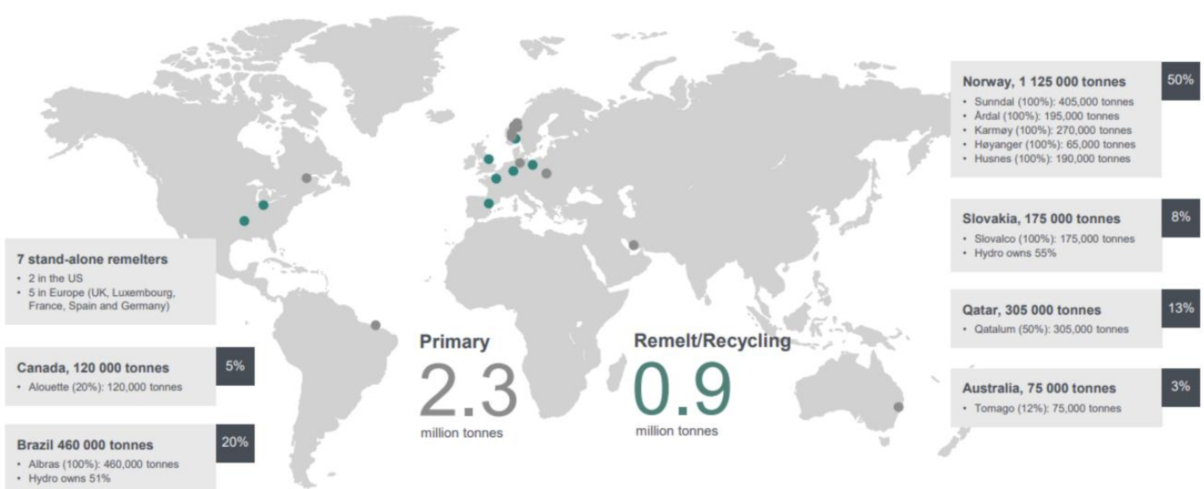


Figure 8: World-wide primary Aluminium production network: Primary metals and metal markets. Source: Hydro

There is an estimated demand of around 250 kg Al per EV (this includes metal for car manufacturing as well as the battery itself) which leads to an absolute demand of 7.5 million tons

[1] Hydro also produces Al outside of Norway making a total production of 2.3 million tons of Al.

in 2030 (assuming the sale of 30 million EVs in 2030, a midpoint between a range of forecasts) [22]. Al is also assumed to play a role in new Li-S batteries with Al-contents of 5-15% [21].

1.8. Silicon

Silicon (Si) is an emerging material in batteries and is used in the anode. Si is found as SiO_2 in quartzite and is the second most abundant element in the earth's crust. World's production of silicon metal in 2015 was 8,100 million tons. 68% of this was produced in China, while Norway produces 4%. 38% of Si in the EU comes from Norway, followed by Brazil (24%), China (8%) and Russia (7%). Silicon metal is listed as a critical raw material in a report from the European Commission in 2017 due to the high import share from China [13]. Recycling of silicon metal is at 0% (over all sectors) [23].

1.9. Summary on raw material needs

Several predictions have been made to assume future battery metal needs. Some of the most recent are presented in Figure 9, Figure 10 and Figure 11. Across all different predictions, the demands for Li are expected to increase significantly (by about 6x until 2030). Cobalt demands are expected to approximately double until 2025, but due to continued efforts in reduction of the Co-content in cathode materials, the demand is expected to eventually reach a plateau. Accelerating growth is predicted for Ni demands, especially class-1 Ni, due to the shift seen in increasing Ni-content in Nickel-Manganese-Cobalt cathodes (Section 2.2).

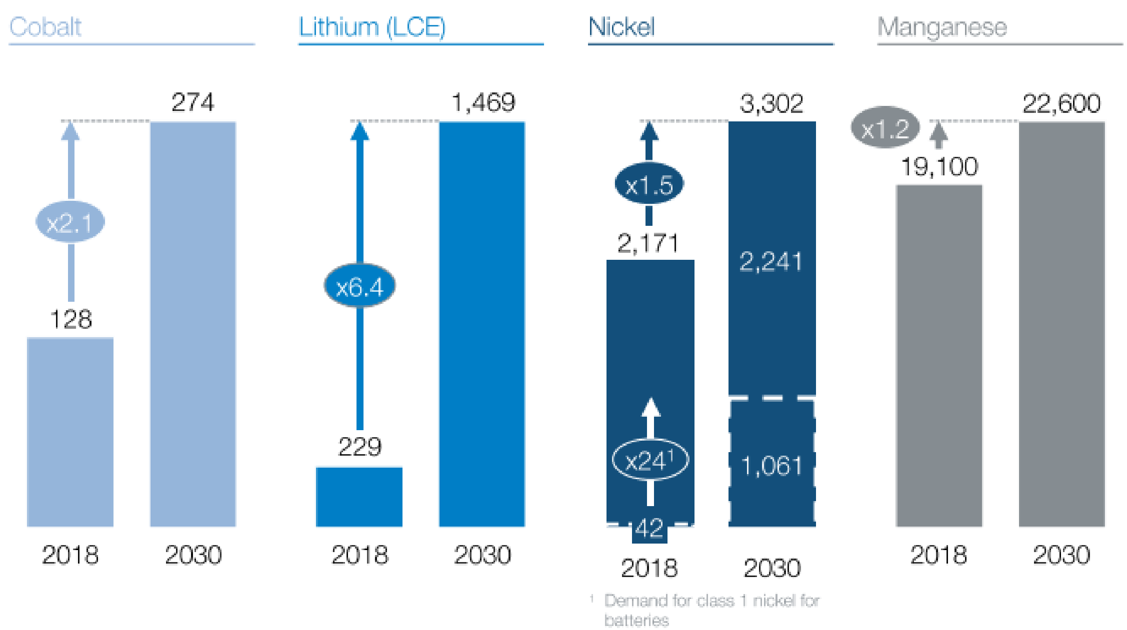


Figure 9: The development in raw material demand from 2018 to 2030 (in kilo tons per year) by McKinsey analysis 2019 [17].

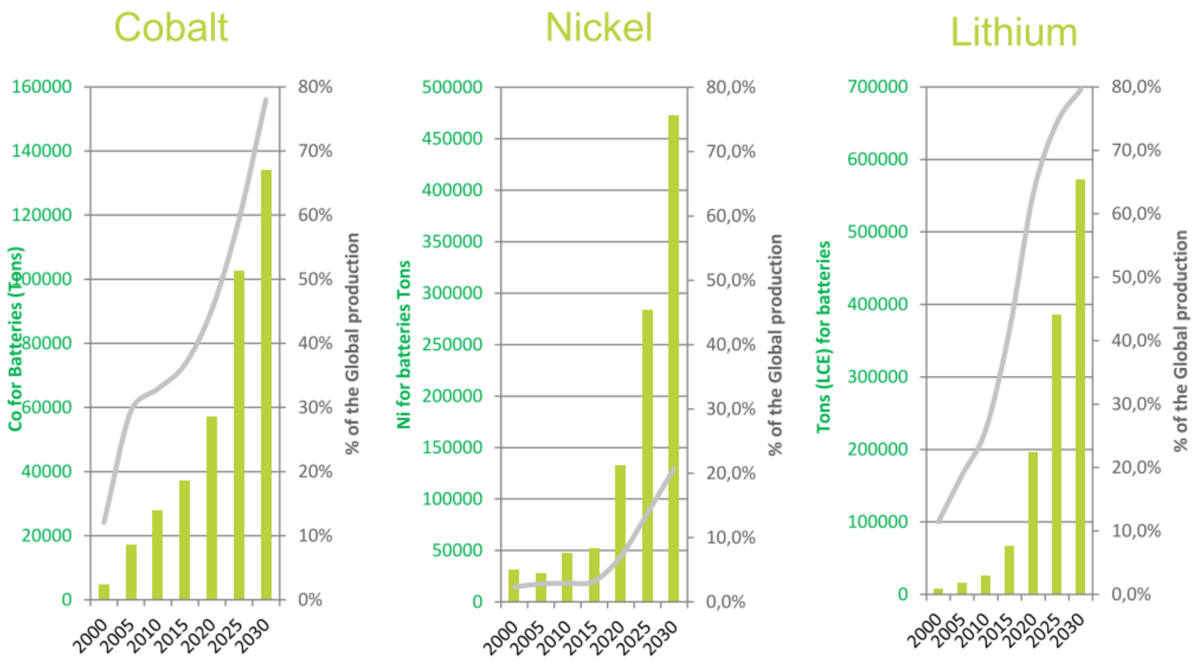


Figure 10: Raw material demand in tons kg, historical and forecast by Avicenne analysis 2019 [24].

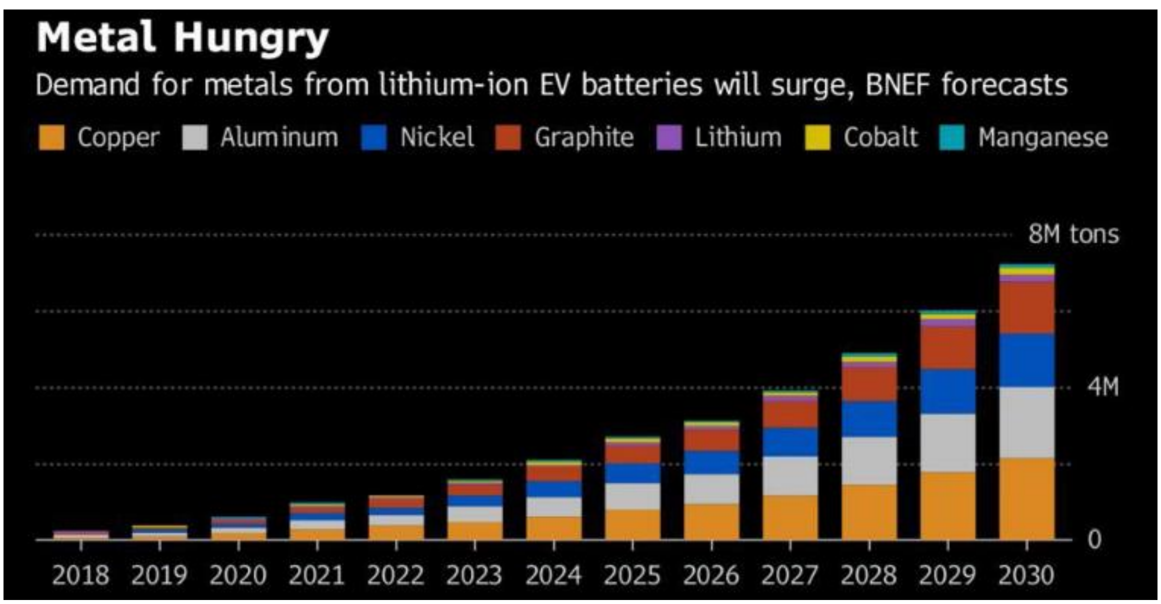


Figure 11: Demand for metals from lithium-ion EV batteries, BNEF forecasts [4]*. Note: Copper includes copper current collectors and pack wiring. Aluminium includes Al current collectors, cell and pack materials and Aluminium in cathode active materials.*

2. The Li-ion battery

A Li-ion battery consists of some main components, where the specifics of each component are tailored to fit the needs of the user. The main components include two electrodes (one cathode and one anode, both deposited on a current collector) for the storage of Li-ions on charge and discharge, an electrolyte in between these for transport of Li-ions while prohibiting the transfer of electrons, a separator to physically separate the two electrodes and a metal casing to isolate the battery from the outer atmosphere. The working principle of the battery is shown in Figure 12, and a schematic of the most common commercial cell types is presented in Figure 13.

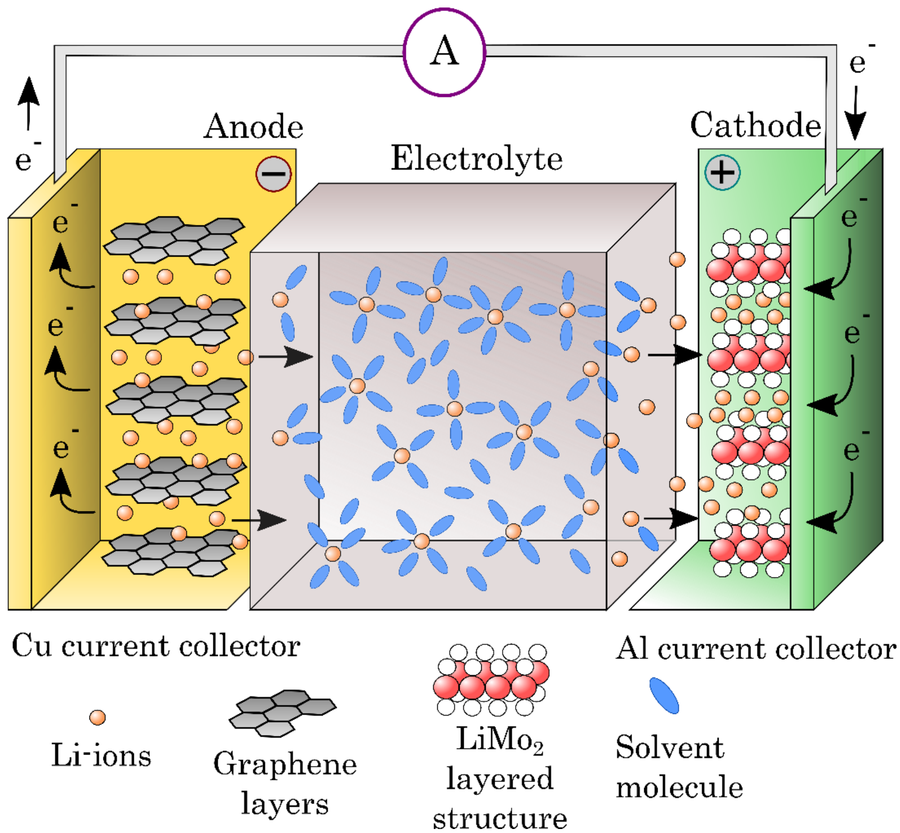


Figure 12: Schematic of a LIB during de-lithiation of the anode. Illustration adapted from Dunn et al. [25]

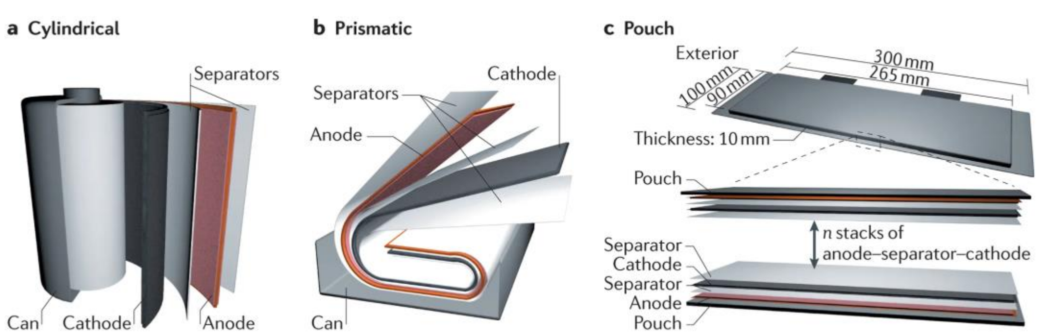


Figure 13: Three representative commercial cell formats [26].

Some of the main performance key factors for a battery are summarized below [27], and will be used to describe the battery technologies in the upcoming sections.

Energy: amount of energy that can be stored in a battery, usually referred to as "energy density". Quantified by Wh/l or Wh/kg (volumetric or gravimetric). Crucial for mobility applications, where volume/weight is an important factor.

Power: amount of power that the battery can deliver, usually referred to as "power density". Quantified by W/l or W/kg (volumetric or gravimetric). Crucial for applications where high power is needed over a shorter period of time, for example power tools, trucks and forklifts.

Capacity: measure of the charge stored by the battery, typically given in Ah or Wh.

The main components of the battery, including their weight percentage of the total battery and some typical chemistries are summarized in Table 1.

Table 1: Main components (by weight) of a Li-ion battery [4].

Cathode: 15-27%	LCO - Li_2CO_3, $LiCoO_2$
	LMO - $LiMn_2O_4$
	LNO - $LiNiO_2$
	LFP - $LiFePO_4$
	NMC - $LiC_{1/3}Ni_{1/3}Mn_{1/3}O_2$
	NCA - $LiN_{0.8}Co_{0.15}Al_{0.05}O_2$
Anode: 10-18%	Graphite - LiC_6
	LTO - $Li_4Ti_5O_{12}$
Electrolyte: 10-16%	Ethylene carbonate
	Diethyl Carbonate
	$LiPF_6$ or $LiBF_4$
	$LiClO_4$
Separator: 3-5%	Polypropylene
Binders: 3-5%	PVDF, SBR
Current collector anode: 12-16%	Cu foil
Current collector cathode: 16-27%	Al foil
Case and terminals: 8-10%	Steel

The battery is often given a name representing what cathode material is used, as this is what varies the most for different areas of use. The anode is most often graphite, but we see that other materials are playing an increasingly important role, either as additives or potential replacements.

2.1. Anode

2.1.1. State of the art materials

Graphite is the most common anode material for LIBs. Good anode materials have a low reduction potential with respect to Li/Li^+ to achieve a high energy density, and graphite is extremely well suited to host Li-ions due to its layered structure allowing for fast diffusion. Table 2 gives an overview of the properties of some common anode materials, but only graphite, LTO and some % of Si (in combination with graphite) are commercially in use today. A summary of anode materials as a function of potential vs. Li/Li^+ and specific capacity is given in Figure 14.

Table 2: Properties of some commonly studied anode materials [1]. *Lithiation and de-lithiation potentials give information on when (de)alloying reactions occur between the host material and Li-ions.*

	Material	Lithiation potential [V]	Delithiation potential [V]	Volume change
Commercial	Graphite	0.07, 0.10, 0.19	0.1, 0.14, 0.23	10%
	LTO	1.55	1.58	0.20%
	Si	0.05, 0.21	0.31, 0.47	270%
Non-commercial	Ge	0.2, 0.3, 0.5	0.5. 0.62	240%
	Sn	0.4, 0.57, 0.69	0.58, 0.7, 0.78	255%

Table 2 shows the lithiation potential where a lower potential means a higher overall potential for the cell, in combination with a cathode material. The volume change of carbon is roughly 10% and represents little challenge, however the large volume change of silicon and other non-commercial materials is one of the main reasons for the slow market penetration. Figure 14 illustrates the large increase in specific capacity by changing or introducing some Si in the anode material.

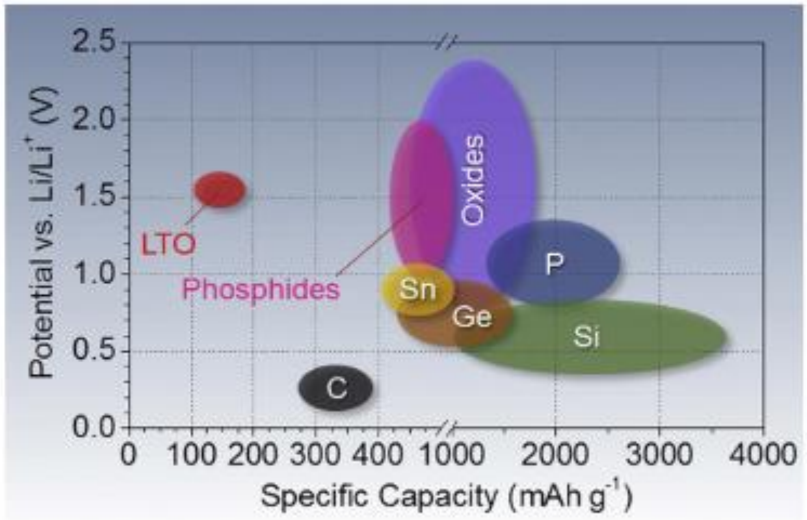


Figure 14: Capacity vs. potential vs. Li for selected anode materials [1].

Carbon

Carbon, and more specifically graphite, has been the main anode material for Li-ion batteries for more than 20 years and will continue to be the leading commercial material for the foreseeable future. There are many sub-categories of carbon, but generally we can divide them into graphitic and non-graphitic.

- **Graphitic carbon** [1]**.** Contains large graphitic grains and achieves close to theoretical capacity (372 mAh/g). Graphitic carbon can be divided into two categories; **Artificial graphite (AG)** (sometimes also referred to as synthetic graphite, SG) and **natural graphite (NG)**. They have about an equal share of the market but exhibit slightly different qualities. NG is typically cheaper to produce, but at the expense of shorter lifetime and lower charging rates compared to AG. NG is made from milled graphite flakes, which are spheronized and purified with hydrofluoric acid or high temperature treatment. The resulting particles are often carbon coated to reduce surface area and obtain a smooth round particle morphology. AG is generally produced by graphitization of byproducts from the petroleum industry, like petroleum coke or coal. This process requires significant mobility of carbon atoms in all dimension and consequently temperatures upwards of 3000°C (which is why the costs increase). However, this results in a product with high purity and more predictable performance.

- **Non-graphitic carbon**
  - **Hard carbon** [1]**.** Small graphitic grains with disordered orientation and are therefore less susceptible to exfoliation. Includes hydrogen remains and nano-cavities. Suffer from high irreversible capacity loss in the early cycles due to cracks and SEI formation in exposed edges. Hard carbons are not able to be graphitized due to crosslinking of crystalline phases. One benefit of hard carbon is that it is generally made from pyrolyzing bio-sourced precursor and therefore constitutes

a renewable source for anode material. It is the anode material of choice for sodium ion (Na-ion) batteries.

- **Soft carbon.** In-between hard carbon and graphitic carbon: disordered, but parallel grains giving higher crystallinity. Soft carbons are often made from the same precursors as AG (coal tar pitch), but pyrolysis happens at lower temperatures (800-1500^{o}C). Unlike hard carbon, soft carbon can be further graphitized to AG at elevated temperatures (2800-3000^{o}C).

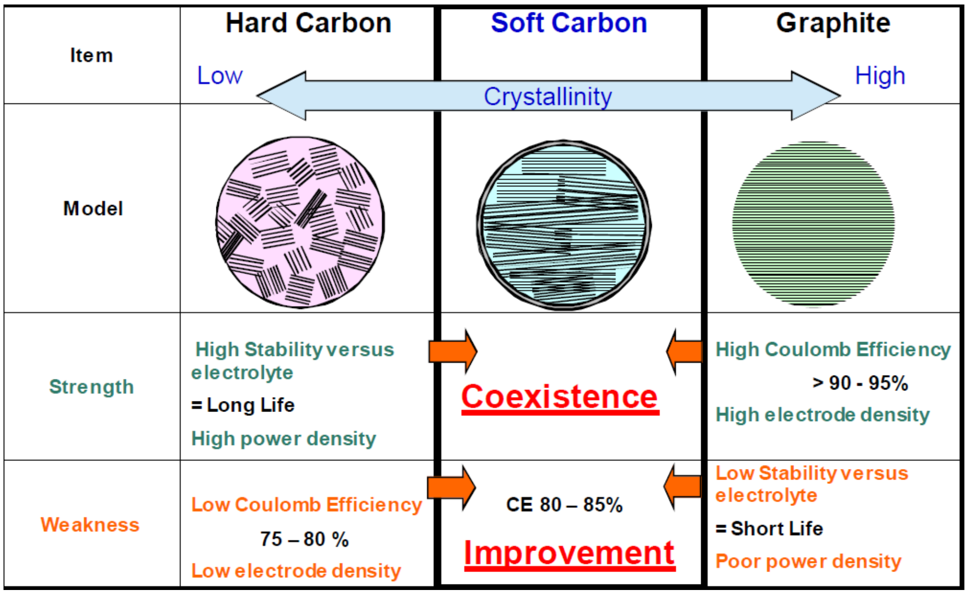


Figure 15: Comparison of properties of Hard Carbon, Soft Carbon and Graphite (from Hitachi Chemicals).

Figure 15 summarizes the main difference between hard carbon, soft carbon and graphite. In terms of capacity to store lithium, AG and NG have the highest reversible capacity due the high crystallinity and lithium intercalation occurring on the graphite edge planes only. AG has higher purity than NG and therefore slightly higher stability/lifetime.

Hard carbon has more exposed edges/crevices where lithium can be stored but is also exposed to electrolyte reduction (solid-electrolyte-interphase (SEI) formation), consuming available lithium and reducing the coulombic efficiency during the first cycles. Soft carbon has areas with crystallinity and areas with rough edges, and therefore serves as bridge between hard carbon and graphite in terms of reversible capacity.

Since hard and soft carbons can store lithium on more sites then graphite (which is limited to edge planes only), they often perform better when charging at higher rates. There is a tradeoff between high reversible capacity and high rate capability, because the available sites needed for fast charging also lead to higher irreversible losses during the initial cycles. Surface coatings are often implemented to reduce the unwanted side reactions, maintain structural integrity and enhance the charge transport of graphitic materials [28].

LTO ($Li_4Ti_5O_{12}$)

LTO combines superior thermal stability, high rate, relatively high volumetric capacity and high cycle life. However, titanium (Ti) is expensive and has both, lower cell voltage and lower capacity of 175 mAh/g than graphite. It should be cycled above 1 V to avoid formation and growth of the passivating SEI layer, as well as having low volume change giving it high stability. LTO is also very safe due to the high potential preventing Li dendrites. However, during aging gas generation can occur due to the interactions between lithiated $Li_4Ti_5O_{12}$, salt and carbonate solvents (CO, CO_2, CH_4, C_2H_4) [1]. LTO is used commercially (e.g. the SCiB, *Super Charge Ion Battery*, by Toshiba), mostly in niche products needing lower capacity, but high power and high cycle life (thousands of cycles). Due to its fast-charging capability (cf. Figure 16) and increased safety, LTO is gaining increasing interest within some transport segments (see Section 3.2).

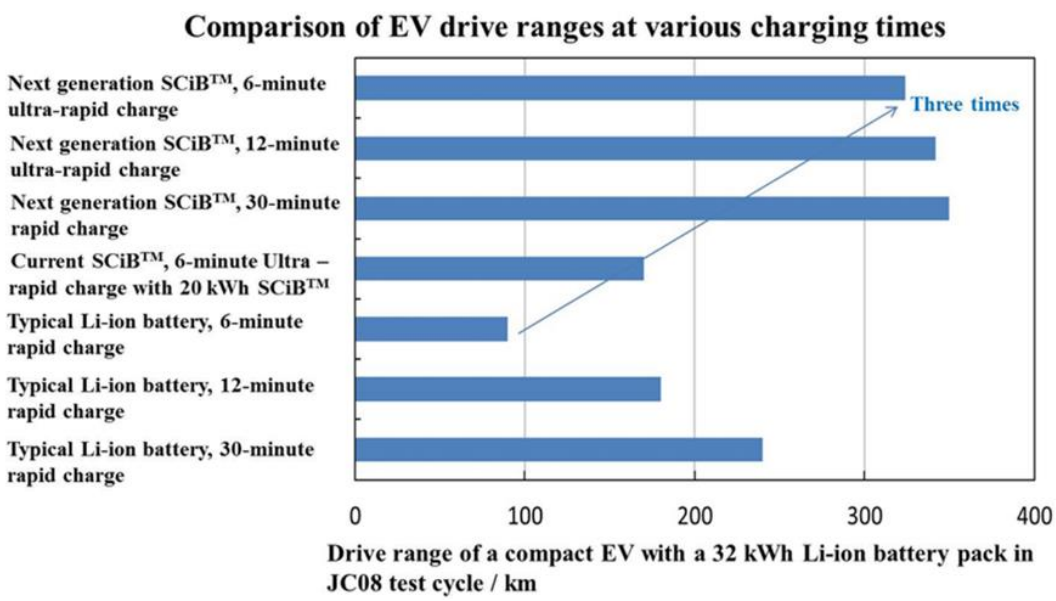


Figure 16: Drive range of a compact EV with a 32 kWh Li-ion battery pack in JC08 test cycle/km [29]*: Comparison of a typical LIB to the SCiB (Super Charge Ion Battery, using an LTO anode).*

Alloying anodes[1]

Alloying anodes have high theoretical capacity and consequently extremely high volume-expansion. This often causes particle fracture and thereby loss of electrical contact and destruction of the SEI layer. Most of these materials are commonly used in combination with graphite as a composite. Some candidates are listed here:

- Silicon is already in use commercially as an additive to boost capacity. It is used e.g. by Panasonic in Tesla EV batteries [30]. Si is quite attractive due to its low average de-lithiation potential, high gravimetric (3579 mAh/g) and volumetric capacity, abundance, low cost, chemical stability and non-toxicity [1]. However, during de-lithiation (when the Si contracts again) Si atoms become disordered, and the particle structure is lost. This is

[1] Elements which electrochemically alloy and form compound phases with Li upon cycling

a major issue due to SEI-reformation and thereby a large loss of Li to inactive structures. This limits the cyclability of Si-based anodes and presents a challenge for the lifetime of these batteries.

- Tin (Sn) has similar properties as silicon, but lower gravimetric capacity and higher electrical conductivity. Sn suffers from easy fracturing, and is not in use commercially. [1]

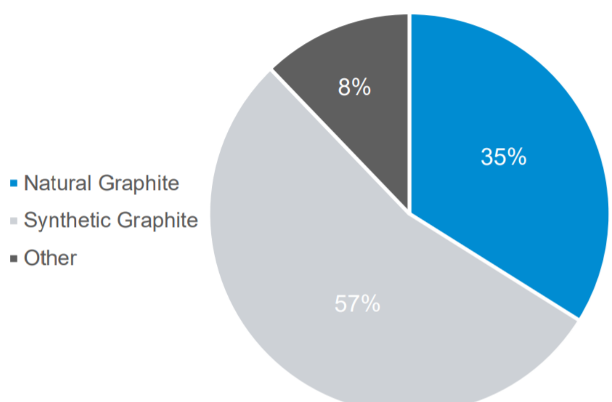
2.1.2. New approaches

There is continuous research into new anode materials with better or complimentary properties than those in use today. A recent development is listed below:

- $TiNb_2O_7$ (TNO) launched by Toshiba in October 2017 [29] based on work from both Goodenough's group [31] and Toshiba research [32]. It has parameters close to LTO, but has slightly better voltage and higher capacity (gravimetric 341 mAh/g, volumetric 1480 mAh/cm^3) making it more suitable for EV applications. They claim it has 3x the amount of energy storage as traditional Li-ion batteries after an ultra-rapid charge of 6 minutes (see Figure 16), but this comparison may be unfair as it is comparing itself to a material not tailored for this fast charge.

2.1.3. Production of anode materials and general trends in the market

Most production of active anode materials has been in China and Japan (84% in 2015 [2]). The global anode market is dominated by only four large producers (Shenzhen BTR New Energy Materials Co., Ltd., Hitachi Chemical, Shanshan Technology Co., Ltd, and Mitsubishi Chemical), holding a market share of 67% in 2019 [33]. Some EU-based companies have shown interest recently, but do not (yet) hold a significant market share. Approximately 40% of total global demand of anode active materials was used in Li-ions batteries for HEVs, PHEVs and BEVs [34].



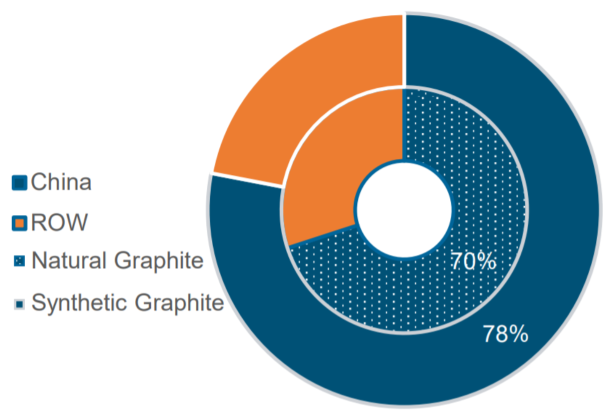


Figure 17: Global LIB anode production (left) and global LIB graphite production by region in 2018 [14].

In 2018, the share between the different anode technologies was dominated by synthetic and natural graphite holding 57% and 35%, respectively of the market, with the main production in China (Figure 17). The 8% share of other materials includes amorphous carbon, Si composites and LTO. Their expected growth forecast based on analysis by Avicenne in 2015 is summarized in

Table 3. While Avicenne, back in 2015, predicted a total anode market volume of 250 ktons by 2025, Research and Markets report China's production of anode materials in 2018 to be already at 192 ktons with an upsurge of over 30% per year, to reach 850 ktons by 2025 [33]. Benchmark Minerals forecasts that the demand for anode materials for LIBs will increase to 1.9 million tons by 2028, further stating that SG and NG (including Si additives) will account for 90% of the anode materials by 2030, pure Si is expected to reach 5% [33]. LTO seems to start to take up an increasingly important role for electric buses (see Section 3.3). However, besides the information from Avicenne presented in Table 3, no further updated details regarding the expected growth of the LTO market share could be found.

Table 3: Expected market volume for anode materials 2015 – 2025 [35] *Numbers are expected to be higher with today's know-how and predictions, but the table shows the expected distribution in 2025.*

Anode	**2015**		**2025**		**Expected growth**
	%	*ktons*	*%*	*ktons*	*times*
NG	49	36.75	24	60	1.6
SG	42	31.5	52	130	4.1
Amorphous carbon	6	4.5	10	25	5.6
LTO	1	0.75	8	20	26.7
Si	2	1.5	6	15	10
Total	100	75	100	250	

2.2. Cathode

2.2.1. State of the art materials

Li-ion batteries are mainly classified according to the cathode material in use. The main Li-ion battery chemistries are NMC (lithium-nickel-manganese-cobalt), NCA (lithium-nickel-cobalt-aluminium), LMO (lithium-manganese-oxide), LFP (Lithium-iron-phosphate) and LTO (lithium titanate, referred to by the anode). LTO is commonly used in combination with LMO or NMC cathodes (but also in combination with LFP for some niche applications). Table 4 summarizes selected properties of those currently on the market. An overview of different cathode chemistries in use today, and a visualization of their capacity relative to each other is shown in Figure 18. Spider graphs in Figure 19 show advantages and tradeoffs between the different battery chemistries in use with the most important parameters are energy density, power density, safety, performance, life time and cost.

Table 4: Types of Li-ion batteries (mainly based on cathode chemistry). LCO is added here, but not used for EVs and the column is therefore grey. Information from batteryuniversity.com and [34].

Cathode	**LMO or NMC**	**NMC-111** ($LiNiMnCoO_2$)	**NCA** ($LiNiCoAlO_2$) 9% Co	**LMO** ($LiMn_2O_4$)	**LFP** ($LiFePO_4$)	**LCO** ($LiCoO_2$) 60% Co
Anode	**LTO** (Li_2TiO_3)	Graphite	Graphite	Graphite	Graphite	Graphite
Usage	Commercial since 2008	Since 2008	Since 1999	Since 1996	Since 1996	Since 1991 (Sony)
Applications	UPS, some EVs, power tools, medical devices	EVs, storage, e-bikes, medical devices	EVs (Tesla/ Panasonic), storage, medical devices	Power tools, medical devices, electric powertrains (often mix with NMC for EVs)	EVs, can replace lead-acid starter battery, portable and stationary storage needing high load currents and endurance like e-buses	Mobile phones, tablets, laptops and other portables. NB! Only cathode not suitable for larger EV-applications.
Voltages [V]	2.4 (1.8-2.85 V/cell)	3.6 (3-4.2 V/cell)	3.6 (3-4.2 V/cell)	3.7 (3-4.2 V/cell)	3.2 (2.5-3.65 V/cell)	3.6 (3-4.2 V/cell)
Specific Energy [Wh/kg]	50-80	150-220 NMC111: 199 NMC532: 205 NMC622: 225 NMC811: 270	200-260	100-150	90-120	150-200 (Specialty cells up to 240)
Charge (C-rate)	1 (up to max 5)	0.7-1	0.7	0.7-1 (up to max 3)	1	0.7-1
Discharge (C-rate)	10	1	1	1 (possible up to 10)	1	1C
Cycle Life*	3000-7000	1000-2000	500	300-700	>2000	500-1000
Thermal runaway [°C]	Safest Li-ion battery	210	150	350	270	150

* Related to depth of discharge, load, temperature

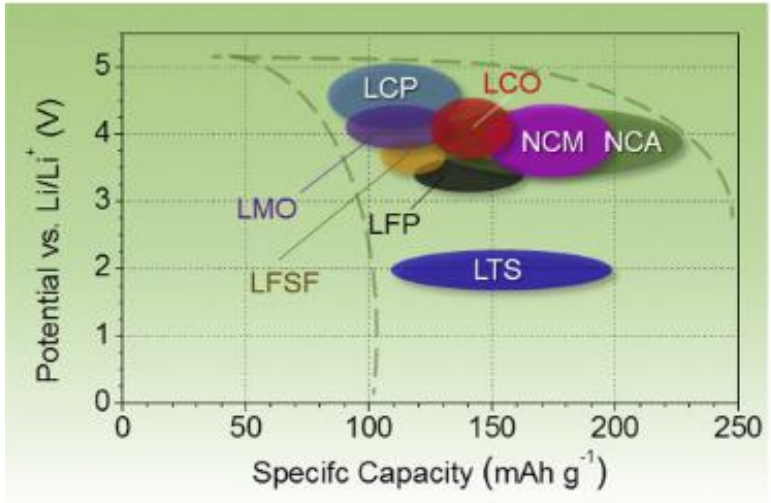


Figure 18: Capacity vs. potential vs. Li/Li⁺ for selected cathode materials [1]*. Additional cathode chemistries in the Figure that are not mentioned in the text are: LTS (Lithium titanium sulfide), LFSF (lithium iron fluorosulfate $LiFeSO_4F$).*

The most used cathode materials today are transition metal oxides due to their high operating voltage (3-5 V vs Li/Li^+) and therefore high storage capability, these will be introduced here:

LCO ($LiCoO_2$)

First commercialized by SONY in 1991 and is still the leading cathode material for portable electronics [36]. It can also be used for smaller EVs. LCO has a high theoretical gravimetric capacity of 274 mAh/g (theoretical volumetric capacity of 1363 mAh/cm^3), low self-discharge, high discharge voltage and good cycling performance [37]. Limitations are the high cost of Co, low thermal stability and fast capacity fade at high current rates or deep cycling. There is a risk of thermal runaway due exothermic release of oxygen above T = 200°C [38], which is a general issue of transition metal oxides, but LCO is the worst of them. Coatings (Al_2O_3, B_2O_3, TiO_2, ZrO_2) can stabilize LCO by reducing mechanical and chemical strain.

NMC ($LiNi_xCo_yMn_zO_2$)

NMC has similar or higher specific capacity than LCO. It has similar operating voltage but lower cost because of the reduced Co content. NMC-111 (referring to a Ni:Co:Mn-ratio of 1:1:1, i.e. $LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2$) is the most dominant cathode material in use today. Efforts continue to further reduce the Co-content (and thus the price), leading to 532, 622, 811 and further down to 9.5.5. One major challenge is that the higher the nickel content, the better the energy density, but the more unstable the battery. When available, information about the specific NMC-type will be given, if not, NMC simply refers to this general cathode family.

LMO ($LiMn_2O_4$)

LMO refers to the spinel-type material $LiMn_2O_4$. Owing to its three-dimensional structure, $LiMn_2O_4$ offers improved ion flow and thus lower internal resistance and improved current handling, enabling fast charging and high-current discharging. Drawbacks are limited cycle and calendar life. LMO has high power, but low capacity and is therefore often mixed with NMC for EVs to have both acceleration and driving range (e.g. Nissan Leaf, Chevy Volt, BMW i3 [39]).

LFP (LiFePO4)

LFP is not a popular choice for PEVs due to a low energy density (like LMO), but offers high stability and higher power capabilities, making it a good choice for large-scale applications such as stationary energy storage or e-buses (especially in China). It is also probably the most sustainable and safe cathode material [40].

NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)

NCA cathodes offer high discharge capacity (200 mAh/g) and long storage calendar life compared to conventional Co-based oxide cathode. Capacity fade is observed at 40-70°C due to SEI growth and microcracks at grain boundaries [41]. NCA cathodes are used commercially by Panasonic in Tesla EVs.

NMO ($LiNi_{0.5}Mn_{0.5}O_2$)

NMO was developed to create cheaper cathodes. It has similar energy density as LCO but reduces the cost thanks to cheaper raw materials. Ni allows higher Li extraction but can also cause lower Li diffusivity resulting in lower rate capability. Adding Co enhances the structural stability, resulting in the development of NMC. This material is therefore not really in commercial use and is not included in any further discussions here.

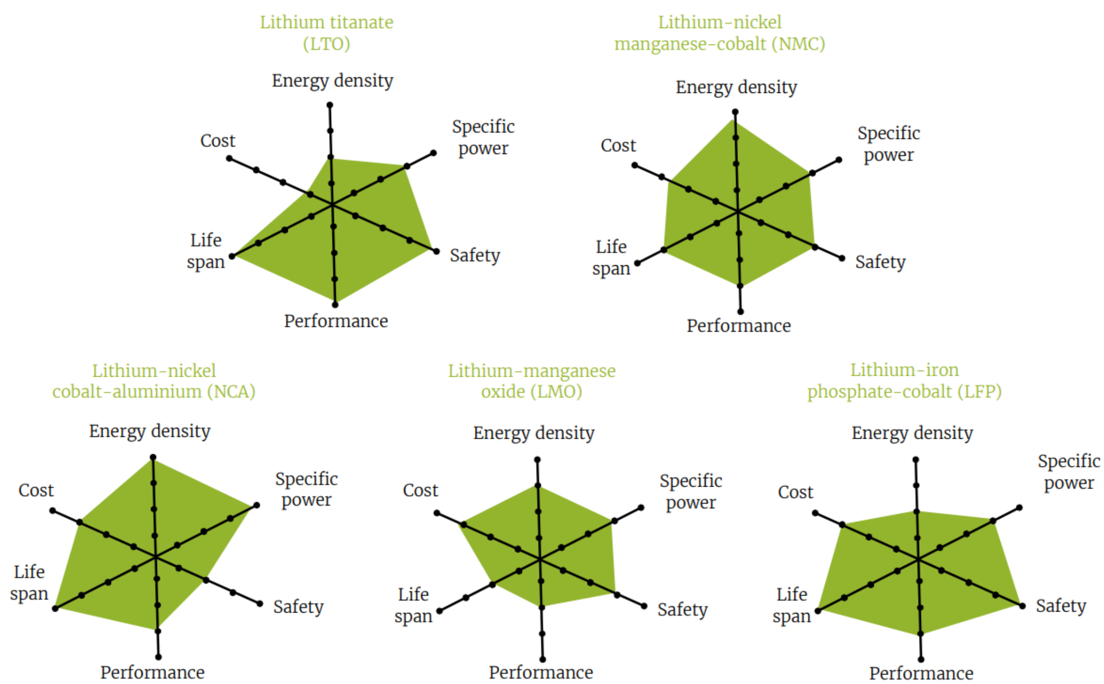


Figure 19: Trade-offs among main Li-ion battery chemistries [42]

A summary of the different cathode chemistries, their specific capacity and average voltage is seen in Table 5.

Table 5: Characteristics of representative intercalation cathode compounds: crystal structure, theoretical/experimental/commercial gravimetric and volumetric capacities, average potentials and level of development [1].

Crystal structure	Compound	Specific capacity (mAh g^{-1}) (theoretical/experimental/typical in commercial cells)	Volumetric capacity (mAh cm^{-3}) (theoretical/ typical in commercial cells)	Average voltage (V) [34]	Level of development
Layered	$LiTiS_2$	225/210 [35]	697	1.9	Commercialized
	$LiCoO_2$	274/148 [36]/145	1363/550	3.8	Commercialized
	$LiNiO_2$	275/150 [37]	1280	3.8	Research
	$LiMnO_2$	285/140 [38]	1148	3.3	Research
	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	280/160 [32]/170	1333/600	3.7	Commercialized
	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	279/199 [33]/200	1284/700	3.7	Commercialized
	Li_2MnO_3	458/180 [39]	1708	3.8	Research
Spinel	$LiMn_2O_4$	148/120 [40]	596	4.1	Commercialized
	$LiCo_2O_4$	142/84 [41]	704	4.0	Research
Olivine	$LiFePO_4$	170/165 [42]	589	3.4	Commercialized
	$LiMnPO_4$	171/168 [43]	567	3.8	Research
	$LiCoPO_4$	167/125 [44]	510	4.2	Research
Tavorite	$LiFeSO_4F$	151/120 [30]	487	3.7	Research
	$LiVPO_4F$	156/129 [45]	484	4.2	Research

2.2.2. New approaches

- Haldor Topsøe (DK) has developed a high-voltage cathode material LNMO (spinel lithium-nickel-manganese-oxide, $LiNi_{0.5}Mn_{1.5}O_4$, not to be confused with layered NMO), delivering similar performance as NCA and NMC chemistries but at a 15-22% lower cost. This material has not been commercialized yet due to the lack of electrolytes able to handle the high voltages (4.7 V) of an LNMO battery, but electrolyte manufacturers have started to report promising results [43].
- NanoOne announced earlier in 2019 their advancements in a new Co-free cathode material, as well as general advancements in their NMC cathode [44]. Their new material is a high voltage spinel (Li, Ni, Mn, element X) but the replacement for Co has not been released. The advancement is expected to complement the arrival of solid-state batteries. The production is at pilot level, and NanoOne is partnered with Volkswagen for their research [45].
- A Chalmers University group has recently published work on Al-batteries, where the anode is made of Al-metal, and the cathode made of an anthraquinone-based organic material. The abundance of Al is a big motivating factor, while high (but not higher than today's LIB) gravimetric and volumetric capacity and safety are some of the other benefits [46].
- As mentioned, LFP batteries normally have too low energy density (90-120 Wh/kg) to be relevant for the personal vehicle market and are predominantly used for buses or energy storage. However, BYD and ETC have introduced manganese into the mix, resulting in a LFMP cathode with a higher energy density (165 Wh/kg). Both cell-producers share a goal of reaching 200 Wh/kg using LFMP combined with a silicon/carbon anode, which would introduce a new cobalt-free battery with decent energy density, as well as being safe, durable and cheap [47].

2.2.3. Production of cathode materials and general trends in the market

The total market demand for cathode materials for Li-ion batteries was 140,000 tons in 2015, and it is estimated that approximately 25% of this was for the use in HEVs, PHEVs and EVs [2]. Newer numbers from Avicenne show that within just three years the market had grown to 350,000 tons in 2018 [24]. Production is dominated by Asia, where China holds the largest market share of 39% (by weight). The largest producer in Europe was Johnsen Matthey (UK) with 2,560 tons of LFP [2]. BASF has recently announced Harjavalta in Finland as their next location for battery materials production (mainly materials for NMC and NCA cathodes, using Nickel and Cobalt from Nornickel's metal refinery, also in Harjavalta) serving the European automotive market (as part of a 400-million-euro investment program) [48]. Start-up is planned for late 2020, enabling the supply of approximately 300,000 full electric vehicles per year with their battery materials. Follow-up investments at several European locations are planned [49].

According to the JRC report from 2018, NMC batteries represent 53% of the total market (based on fleet between 2011 and 2017), NCA 47% and the remainder is LFP or other chemistries. These numbers exclude China, as their fleet has historically been mostly LFP [34].

The expected market shares for 2018 to 2030 based on reports from Avicenne Energy [24], Roskill [7], McKinsey [50], Bloomberg New Energy Finance (BNEF) and BMO (Bank of Montreal Capital Markets) [16] are summarized in Figure 20. According to Avicenne's scenario, only NMC-cathodes are expected to see growth (of 46% from 2018 to 2030), while all others see a decline in usage.

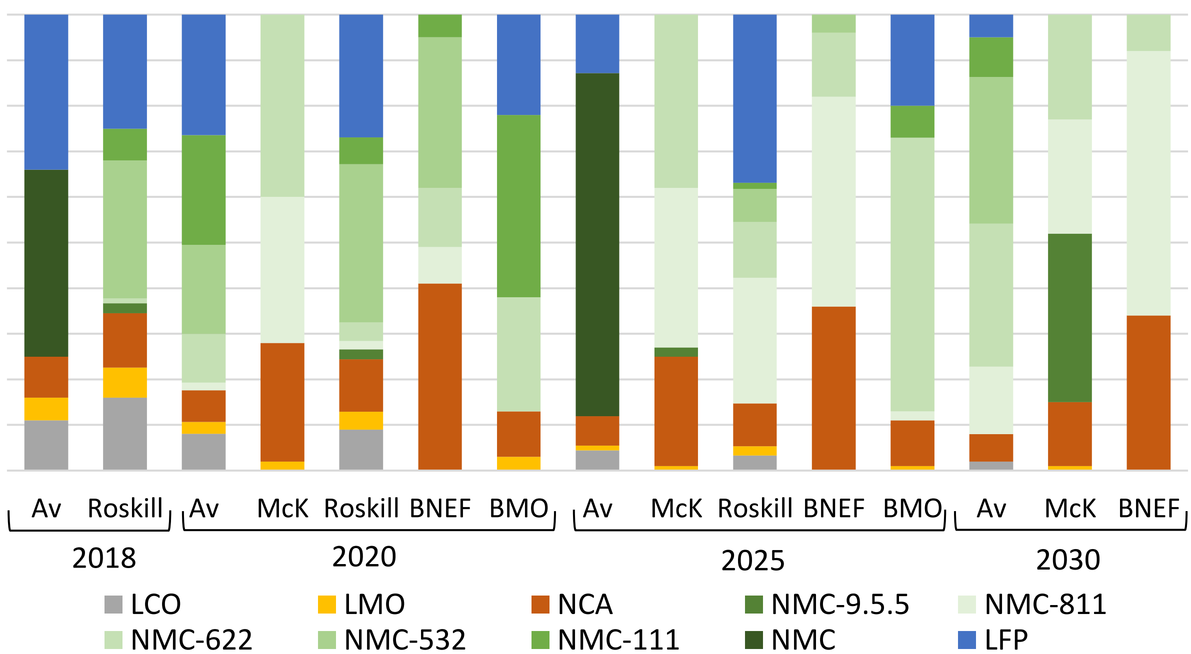


Figure 20: Expected developments of the market share of different battery chemistries. A summary combing reports from Avicenne (Av), Roskill McKinsey (McK), BNEF and BMO. Avicenne numbers for 2018 and 2025 does not specify NMC-chemistry and is therefore only listed as NMC. Values exclude China. The original graphs from the individual reports and a corresponding table can be found in Appendix A2. [7], [24], [50], [16].

The cathode market in general is expected to grow dramatically over the next 10 years, which can be seen in Figure 21. Here it is also very clear that China is ahead of us on this journey, but it is expected that the rest of the world will catch up, because subsidies and incentives in China slow the market down again.

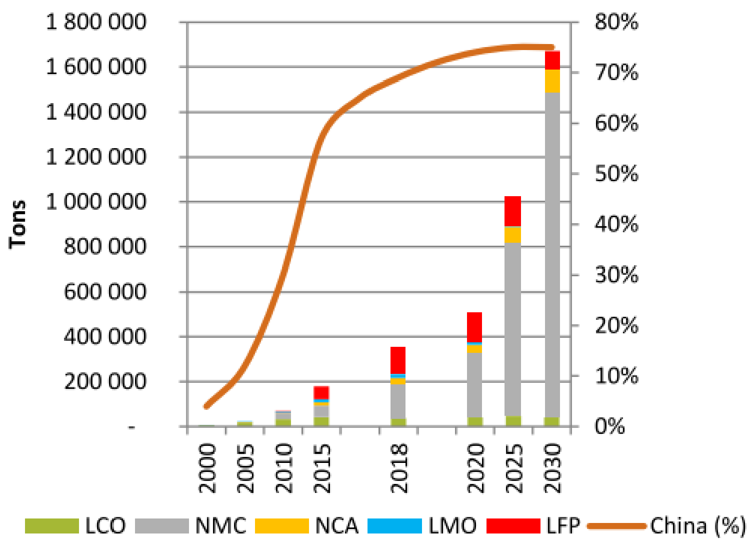


Figure 21: Cathode active materials by chemistry, growth from year 2000 to 2018 and future is forecast based on assumptions presented by Avicenne in 2019 [24].

2.2.4. Raw material demands into cathode chemistries

Where information on compositions of batteries was available, data and numbers are presented here: Table 6 gives an overview of g/kWh battery capacity combing several sources, while Table 7 also includes metal for packing and BMS. Figure 22 gives the weight percentage of materials per cathode chemistry, including oxygen.

Table 6: Required amounts of raw materials in g/kWh battery capacity. Numbers from ref [34] *and* [4] *are based from readings of bar-charts and may therefore contain small errors.*

	Element	**NMC** (ass. 111)	**NMC111**	**NMC333**	**NMC442**	**NMC622**	**NMC811**	**LFP**	**NCA**	**LCO**	**LMO**
	Ref	[51]	[34]	[4]	[4]	[34]	[34]	[51]/[4]	[34]	[34]/[4]	[4]
Cathode	Li	177	139	125	156	124	113	119/62	109	111/109	104
	Ni	459	391	343	442	638	748	0	754	0	0
	Mn	432	366	317	411	196	86	0	0	0	953
	Co	467	391	354	437	209	92	0	145	954/973	0
	Fe	0	0	0	0	0	0	1030/?	0	0	0
	P	0	0	0	0	0	0	478/?	0	0	0
	Al	0	0	0	0	0	0	0	50	0	0
Anode	Graphite	1,626						1,560			

Table 7: Weight percent of materials in a 20kWh pack (including metals for cell, pack housing, BMS). This does not consider organic components (solvents), separator, anode material, binders, plastics. Also excludes oxides in cathode. [52]

Element	LTO (anode)	NMC [%]	NCA [%]	LMO [%]	LFP [%]
Li	3.5	1.9	1.6	1.3	1.5
Al	18.0	12.8	13.9	19.3	12.8
Cu	2.0	12.1	13.0	17.8	5.4
Ni	0.4	6.3	10.6	0.1	0.1
Co	-	3.1	1.9	-	-
Mn	-	5.7	-	9.5	-
Fe	13.9	8.0	8.0	8.0	19.4
P	6.9	3.0	-	-	9.4
Total	44.6	53	49.1	56.1	57.4
Wh/kg	52.4	139.5	133.6	114.9	83.2

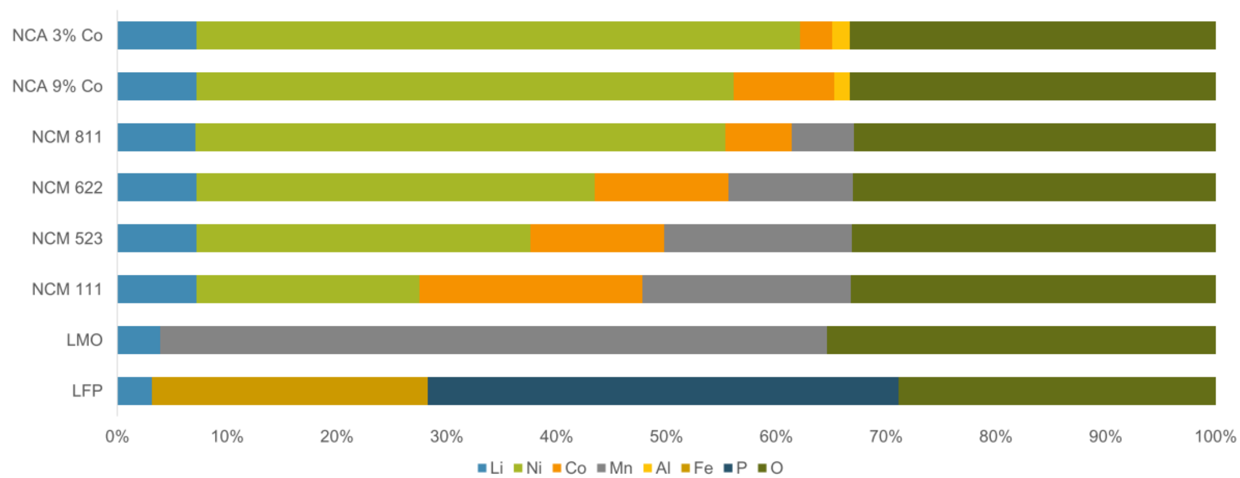


Figure 22: Material composition of major cathodes by weight, highlighting the raw material demand of each [7].

2.3. Electrolytes

The electrolyte separates the two electrodes in the battery and allows for the movement of Li-ions between anode and cathode. The electrolyte in a standard state-of-the-art battery is a liquid and consists of a Li-salt(s) dissolved in appropriate solvents. Ongoing research goes into developing other types of electrolytes, such as ionic liquids, polymers or solid ceramics.

The global market for electrolytes for all applications of Li-ion batteries was slightly bigger than 62,000 tons in 2015 and the revenues generated were B$ 0.9. Like cathode and anode active materials, the production of electrolytes for Li-ion batteries is dominated by Asian suppliers, with China currently producing close to 60 % (by weight) of the total market, as seen in Figure 23.

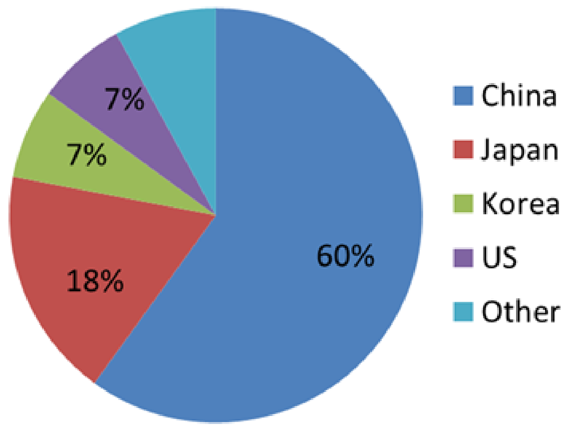


Figure 23: Electrolyte production in 2015 [35].

The market for electrolytes is expected to grow from the current 62,000 tons to more than 235,000 tons in 2025, with the automotive share increasing from current ca. 33% to ca. 50% of the market.

2.3.1. The solvents, salts and ionic liquids

Aqueous electrolytes are not stable in the wide electrochemical window of LIBs. Because of this, non-aqueous electrolytes have been in use ever since the start of the commercialization of LiBs in the early 90s. However, even common non-aqueous electrolytes are not completely stable, and the formation of a passivating film (SEI) is necessary for stable battery operation.

Non-aqueous electrolytes often consist of cyclic carbonates, like ethylene carbonate (EC) and propylene carbonate (PC). These cyclic carbonates are ideal for the film formation necessary for stable operation and are often combined with linear carbonates, which provide optimal viscosity. Typical linear carbonates are diethylene carbonate (DEC), dimethyl carbonate (DEM), and ethyl methyl carbonate (EMC)[53]. One typical electrolyte compositions can be 1.0 M $LiPF_6$ (3:7) EC:EMC.

There are many available lithium salts as shown in Table 8, but the most used is $LiPF_6$ (Lithiumhexafluorophosphate) due to its good overall properties. However, there are several drawbacks with $LiPF_6$, most notably the thermal stability and moisture sensitivity. The thermal stability is very poor above 55 °C and the extreme moisture sensitivity can initiate hydrolyzation to form HF [54]. With reference to Table 8, the best alternative seems to be LiTFSI ($LiC_2F_6NO_4S_2$, Lithium bis(trifluoromethanesulfonyl)imide), but unfortunately this salt suffers from severe aluminum corrosion and is only usable in cells were the upper voltage limit is less than 3.6 V. The corrosion was found to be somewhat suppressed by a mixture of $LiPF_6$ and LiBOB ($LiB[C_2O_4]_2$, lithium bis(oxalato)borate)[55]. LiBOB is itself a promising salt with improved thermal stability and ability to form films protecting against exfoliation, even in pure PC containing electrolytes. However, it suffers from poor solubility, and is therefore mostly used as an additive rather than a main salt [56].

Table 8: Comparison of different lithium salts. Adapted from [57]. (LiTf: Lithium trifluoromethanesulfonate).

Properties	From best		→		to worst
Ion mobility	LiBF4	LiClO4	LiPF6	LiAsF6	LiTf	LiTFSI
Ion pair dissociation	LiTFSI	LiAsF6	LiPF6	LiClO4	LiBF4	LiTf
Solubility	LiTFSI	LiPF6	LiAsF6	LiBF4	LiTf	
Thermal stability	LiTFSI	LiTf	LiAsF6	LiBF4	LiPF6	
Chem. inertness	LiTf	LiTFSI	LiAsF6	LiBF4	LiPF6	
SEI formation	LiPF6	LiAsF6	LiTFSI	LiBF4		
Al corrosion	LiAsF6	LiPF6	LiBF4	LiClO4	LiTf	LiTFSI

The thermal challenges with organic electrolytes are one of the reasons **ionic liquids (IL)** present an interesting alternative. ILs are basically molten salt liquids (melting points < 100°C) containing only ionic species. These usually contain a bulky asymmetric cation (e.g. imidazolium), and different inorganic or organic anions (e.g. TFSI, FSI (bis(fluorosulfonyl)imide)). They are much safer than organic electrolytes due to low flammability and almost no volatility, but suffer from high cost, high viscosity and low conductivity at low temperatures [54] and thus have not been commercialized yet.

2.3.2. Solid-state electrolytes

One emerging technology promising to solve the issues with liquid electrolytes and increasing battery safety, are solid-state electrolytes. These come (in theory) with a large list of advantages, such as (i) the mentioned increase in safety combined with a longer lifetime (due to the slower reactivity of solids; most common ageing effects in LIBs are linked to liquid electrolytes), (ii) possible operation at higher and lower temperatures, (iii) high power capability (possibility for fast cycling), (iv) increased energy density (only a thin layer of solid, replacing the liquid electrolyte and the separator), (v) the possibility of the use of next-generation anodes such as metallic lithium and (vi) high voltage cathodes (current problem: oxidation of electrolyte).

One of the problems of liquid electrolytes, in addition to its thermal stability as mentioned above, is the formation of dendrites which could potentially cause a short circuit and initiate a thermal runaway. A solid electrolyte can in theory prevent this, and in addition facilitate the use of pure lithium metal as anode, which would improve the energy density drastically. However, some studies have shown that growth of lithium still occurs through a range of solid electrolytes [58] and that lithium can deposit along the grain boundaries and grow until the battery is short circuited [59]. In addition to this, some issues that need to be solved with regards to solid electrolytes is the ionic resistance, low power density, and high production cost [60].However, there are many challenges to overcome before solid-state electrolytes become commercially viable.

Liquid electrolytes have conductivities in the range of 10^{-2} S cm^{-1}; however, the transport number for lithium is only 0.5. Solid electrolytes have transfer number of unity, and would in that sense only need an ionic conductivity of 10^{-3} S cm^{-1} to compete with liquid electrolytes in terms of energy density [61].

There are many different types of solid electrolytes being investigated for the potential use in LIBs, some of the more common ones are summarized in Figure 24.

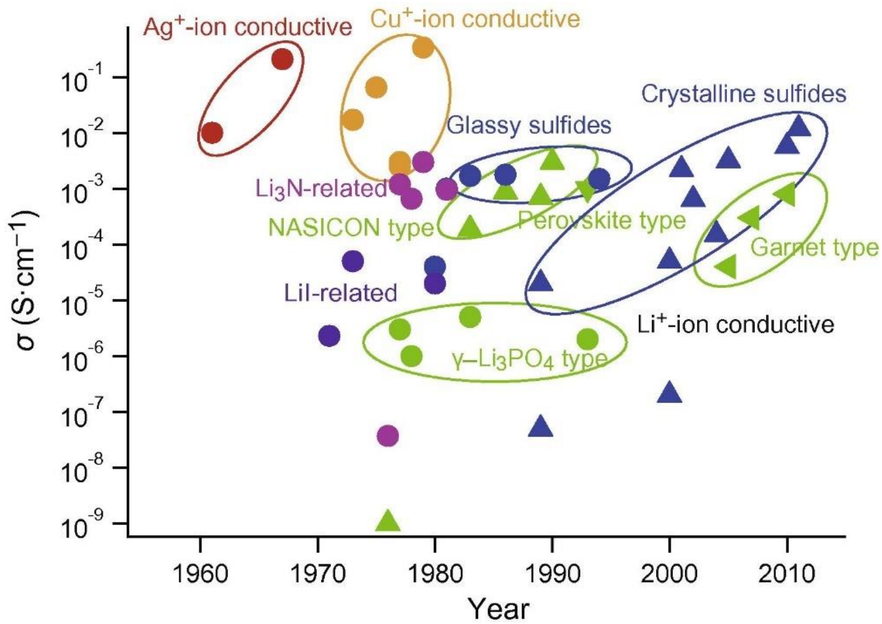


Figure 24: Progress of solid electrolytes in terms of ionic conductivity [61]

Among the electrolytes shown in Figure 24, sulfides are the ones which show most promise with regards to high ionic conductivity. Some functional solid-state batteries with sulfides are listed in Table 9. From this we see that some can approach liquid electrolytes in terms of energy density, but long-term performance is still a challenge as usually no more than 100 cycles are reported, at best.

To compare liquid and solid electrolytes, Table 10 shows present day liquid electrolytes with solid state and estimates future energy densities. As we see, many of the values for liquid electrolytes with lithium metal and solid-state batteries are missing, simply because the data is not currently available in the literature. Theoretical calculation is made for future SSEs based on low density electrolytes (such as sulfides and polymers) and high-density electrolytes (such as garnet LLZO).

From these calculations it seems that low density SSE, such as the sulfides, coupled with pure metal anode provides the best choice to compete with present (and future) liquid electrolytes.

Table 9: Solid state batteries with sulfides. Adapted from [62].

Chemistry	Energy density Wh/kg	Degradation rate	Year and reference
$Li_4Ti_5O_{12}$/LPS-LGPS/$LiCoO_2$	44	Not reported	2015 [63]
Graphite/LGPS-LPS/$LiNbO_3$ coated $LiCoO_2$	180 (435 volumetric with electrode 600um)	Not reported	2018 [64]
Graphite/Li_6PS_5Cl/NMC622	184 (432 volumetric)	20 cycles	2018 [65]
Lim/LiI-Li_3PS_4/LZO-coated NCA	260 (based on cathode composite, not including anode)	99.6 within last 50 cycles	2016 [66]
Graphite/Li_3PS_4/$LiNbO_3$-coated NMC	155 (excluding current collector and package)	Only reported for half cells	2017 [67]
Graphite/Li_2S-P_2S_5 (80:20 mol%)/Li_2O-ZrO_2 (LZO) coated NCA		80% at 100 cycles	2014 [68]

Table 10: Comparison of current/future (expected performance) liquid/solid-state electrolytes [62].

Technology	Gravimetric density [Wh/kg]	Volumetric density [Wh/L]	Cost [$/kWh]	CE	Manufacturability
Current liquid electrolyte	260	732	150	99,99	Gigafactories operating
Future liquid electrolyte (no lithium metal)	400	1200	100	99,998	Multiple gigafactories planned
Future liquid electrolyte (with lithium metal)	475	1300	N/A	N/A	N/A
Current SSB (low density SSE)	155	N/A	N/A	70	N/A
Future SSB (low density SSE) (based on theoretical value of low-density electrodes such as sulfides and polymers with lithium metal)	480	N/A	N/A	N/A	N/A
Future SSB (high density SSE) (based on theoretical value of garnet type electrodes, such as LLZO)	375	N/A	N/A	N/A	N/A

As mentioned above, all-solid-state batteries are a promising technology, offering numerous advantages and several companies are working on the commercialization [45]. However several challenges still need to be overcome before they will be commercially available (for a more detailed insight see [69]). The most promising materials classes at the moment (based on patents by e.g. QuantumScope/VW) seem to be sulfides and garnet-type materials.

2.4. Other parts of the battery

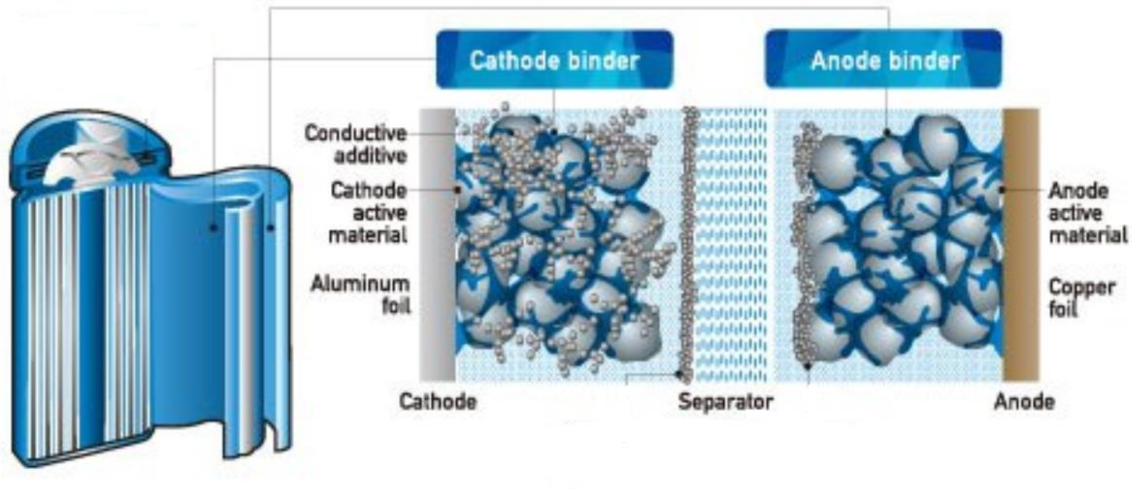


Figure 25: Illustration of a LIB with focus on separators, binder materials and current collectors [69].

2.4.1. Separators

Separators are a class of membranes which are used for the physical separation of the anode and the cathode (Figure 25). They are moistened with electrolyte and thus allow the Li-ions within the electrolyte to flow between the two electrodes, whilst blocking the electrons to prevent short-circuiting. Separators are required to be highly porous, good electronic insulators and possess high mechanical stability. They are commonly made from polymers (e.g. polyethylene (PE) or polypropylene (PP)), ceramics or polymer/ceramic blends.

Separators for LIBS commonly have a pore size between 30 to 100 nm, and a recommended porosity of about 30–50%. This allows the separator to hold enough liquid electrolyte and allows the pores to close in case of overheating, making the separator act as a fuse. E.g. the separator melts when the core reaches a certain temperature. This stops the transport of ions and effectively shuts down the cell, avoiding a thermal runaway [69].

Most batteries for small-scale applications (i.e. mobile phones and tablets) have single-layer PE separators. Larger industrial batteries deploy trilayered separators that provide enhanced fuse protection on thermal extremes and on multi-cell configurations, commonly consisting of PE and PP polypropylene. Figure 26 illustrates a PP/PE/PP trilayer separator consisting of PE in the middle, sandwiched by outer PP-layers. While the inner PE layer shuts down at 130°C by closing the pores, the outer PP layers stay solid and do not melt until reaching 155°C.

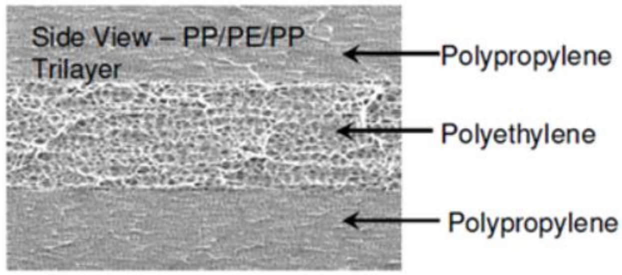
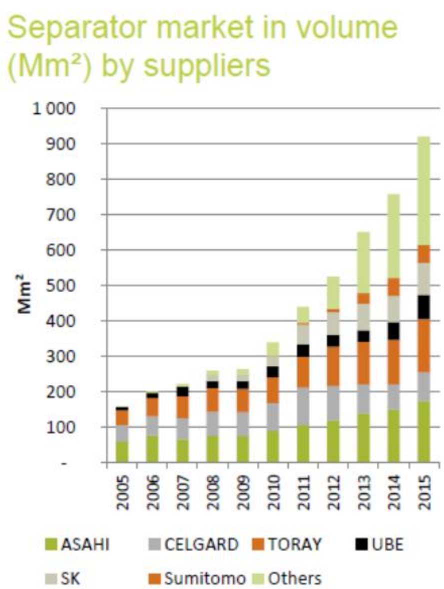


Figure 26: Trilayer separator for enhanced safety [69].

In general, the separator should be as thin as possible to not add dead volume, but still provide enough strength to prevent stretching and offer good stability throughout the lifetime of the battery. There is a trend towards thinner separators: thickness of 25.4 µm used to be common, but now even separators with a thickness of 12 µm are available without significantly compromising the properties of the cell. The separator (including the electrolyte) only makes up about 3 percent of the cell content in modern LIBs.

The total market for separators for all applications of Li-ion batteries was approximately 900 Mm^2 in 2015 and revenues generated were B$ 1.1. Approximately 30% of the global separator market volume or ca. 300 Mm^2 is supplied for production of automotive Li-ion battery cells [35].

Figure 27 shows an overview of the growth in the separator market for Li-ion batteries from 2010, and who the major manufacturers are. It is expected that the separator market for Li-ion batteries will continue to grow steadily with annual growth rate (CAGR) of 12% reaching ca. 2700 Mm^2 in 2025. A major contribution to this growth will come from the needs of electric vehicles and buses in addition to the personal vehicle growth.



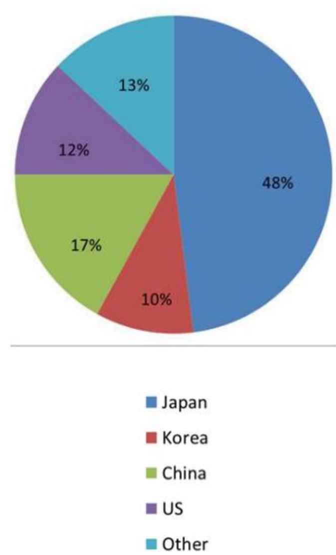


Figure 27: Separator producers and market in 2015 [35].

2.4.2. Current collectors

Aluminium foil is used as a current collector on the cathode side (see Figure 12 and Figure 25). Market leaders in Al-foil production for battery applications are Sumitomo Light Metal Industries (JP) and Nippon Foil Mfg. (JP) [35]. Copper foil is used as a current collector the anode side. Market leaders in Cu-foil production for battery applications are Furukawa Electric (JP), Nippon Foil Mfg (JP), Nippon Denkai (JP) and LSMtron [35]. More details on Cu and Al were given in Section 1.6 and Section 1.7 respectively.

2.4.3. Binders

Binder materials are responsible for holding the active material particles within the electrode of a lithium-ion battery together to maintain a strong connection between the electrode and the contacts (see Figure 25). These binding materials are normally inert and do not contribute to the electrochemistry but play an important role in the manufacturability of the battery. The binder usually constitutes a few percent of the total electrode mass.

Binders must be flexible, insoluble in the electrolyte, chemically and electrochemically stable and easy to apply to the electrodes. Binders for the positive cathode also need to be resistant to oxidation. A common binder material for the cathode is polyvinylidene fluoride (PVDF), whereas a common anodic binder material is styrene-butadiene copolymer (SBR). As electrode materials advance, binder materials that improve the performance of the new electrode materials are also required. Silicon and other alloying anode materials will undergo a larger volume change during charge/discharge and will require a more flexible binder material to support these volume changes.

PVDF is known to be superior in electrochemical and thermal stability and is well suited for the cathode materials which undergo little volume change. SBR is a relatively flexible polymer which is known to improve the mechanical stability. SBR can also improve the adhesion to the current collector of aqueous processed electrodes.

The type of binder used will also dictate the use of solvent to prepare the electrode slurry. PVDF for example is a non-aqueous binder which cannot be dissolved in water (PVDF is typically dissolved in NMP, see Section 2.4.4). Aqueous binders have drawn more and more attention in recent years because of the advantages of low cost and environmentally friendly process [70]. Na-carboxy methyl cellulose (Na-CMC) is a typical aqueous binder used for anode materials, which might become more predominant.

2.4.4. Solvents

Solvents are used in the electrode fabrication process, illustrated in Figure 28, to dissolve the respective binder materials.

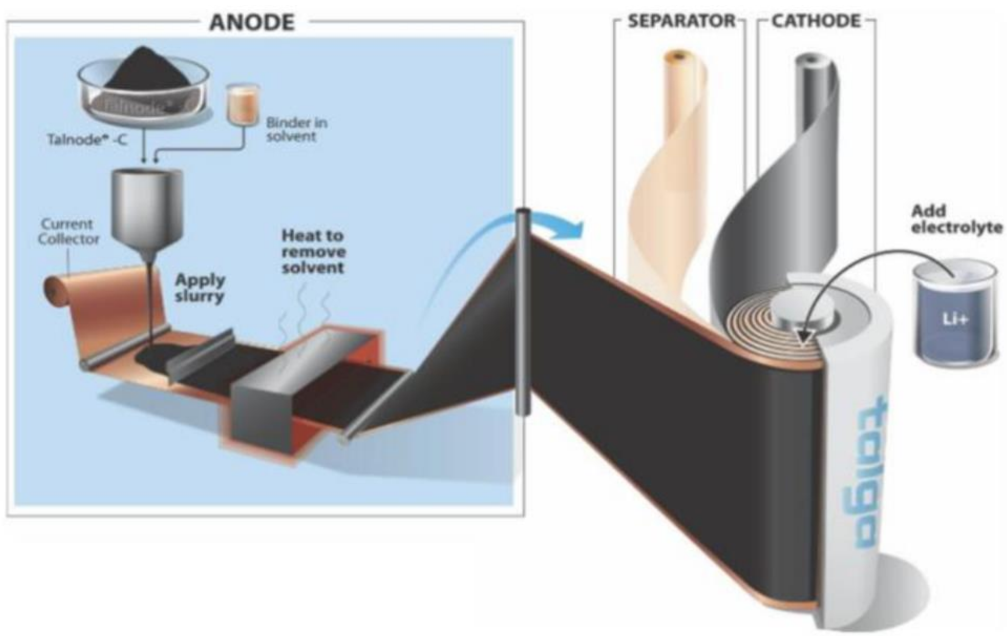


Figure 28: Illustration of the role of the solvents in the electrode fabrication process [69].

Current manufacturing processes employ a solvent based slurry mixing/coating method with *n*-methyl-pyrrolidone (NMP) as the solvent of choice. This is due to stringent solvation and dry atmosphere requirements. The final LIB does not contain NMP, because it is essentially removed from the electrodes during the drying process. NMP is collected, reused for cleaning of the equipment and finally sent for recycling [71]. NMP has recently been identified as a known reproductive toxicant, and as a result, its use is increasingly restricted in the E.U., North America and Japan[1]. In addition to escalating the potential liability and environmental repercussions for its use, the use of NMP is partially responsible for the high of the costs of lithium ion batteries, where it can be responsible for over 50% of the processing costs [72].

Consequently, there is a large drive towards “greener” solvents, which could also be economically beneficial. Alternative solvents, including water, have been tested, and much of the research community have shifted to the use of aqueous slurry preparation. This proves to be easier for anode materials compared to cathode materials.

3.4.6 Battery management system (BMS)

Even with progress in battery chemistries and materials, effective and dependable battery management systems (BMSs) are still needed for the condition monitoring, charge/discharge regulation, thermal control, cell balancing, health prognosis, and safety protection of large-scale battery energy storage.

Without appropriate BMSs, catastrophic hazards and premature failure, such as thermal runaway, may occur owing to poor electrical and thermal operating and maintenance practices.

[1] Was placed on the REACH list in 2018 by the European Commission

Battery management thus plays a critical role in the integration of battery energy storage into the electric grid in terms of performance, safety, reliability, and economy [71].

The main functions of a BMS include:

- data acquisition: the measurement and collection of data on current, voltage, temperature, etc.
- state estimation: high-accuracy gauging of SOC, state of power (SOP), state of health (SOH), state of temperature, etc.
- charge/discharge control: charge current/voltage regulation, power electronics interface, etc.
- cell balancing: passive or active state-of-charge and voltage equalization
- thermal management: control of the maximum temperature and temperature deviation among cells inside a battery pack
- safety protection: hardware setup for avoiding overcharge/overdischarge and overheating, as well as hardware/software redundancy for proactive fault diagnosis/isolation and alarming.

2.5. Main players in Li-ion battery value chain

In Figure 29, an overview of the main players involved in the Li-ion battery value chain is given. The following analysis is taken from the EMIRI technology roadmap for 2019 [27]: "As one can see, Europe is strong in research, manufacturing of active materials, applications and recycling, but is lacking capacity in cell Manufacturing Equipment Testing Equipment and pack manufacturing – although more European organizations are increasingly upscaling pack manufacturing capacity. Although Europe is preparing for the growing battery markets with "Giga" manufacturing plants utilizing imported technologies and EU know-how, China has already taken the lead."

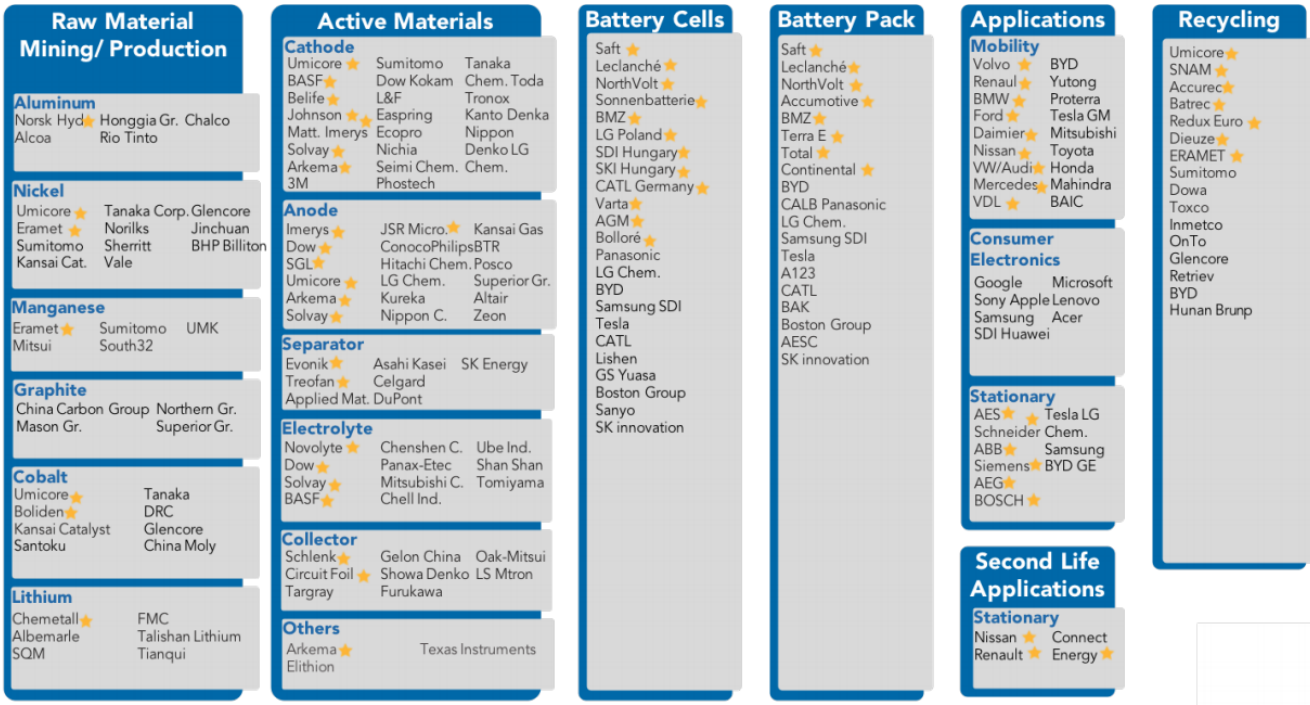


Figure 29: Battery value chain and main players. European organizations are market with a star [27].

2.6. Battery cell production

Between 2010 and 2018 the battery demand grew by 30 % annually and reached a volume of 180 GWh in 2018. The market is expected to continue the growth with an annual increase of 25 % to reach the volume of 2,600 GWh in 2030 [17]. This means that a great number of new battery factories with GWh-capacities will be built and established over the next years.

Today, an estimated 350 GWh of cell production capacity is in operation. Another 510 GWh of capacity is announced through 2025, totaling 860 GWh of cell production capacity of which 60% will be located in China. To meet the demand of 2,600 GWh in 2030, however, another 1,700 GWh of capacity is required. Based on current investment levels, an additional investment volume of $140 billion until 2030 would be needed to meet the demand [17]. The numbers and the estimation of the battery capacity need in 2030 varies extremely, depending on assumptions on the implementation of electrical cars in various countries and political incentives. Figure 30 shows the distribution of battery giga-factories in 2018, with expected sites and distributions in 2023 and 2028. Most of the battery production will still be in Asia with China as the main actor (with 57% of the total market), but the European fraction of gigafactories will increase.

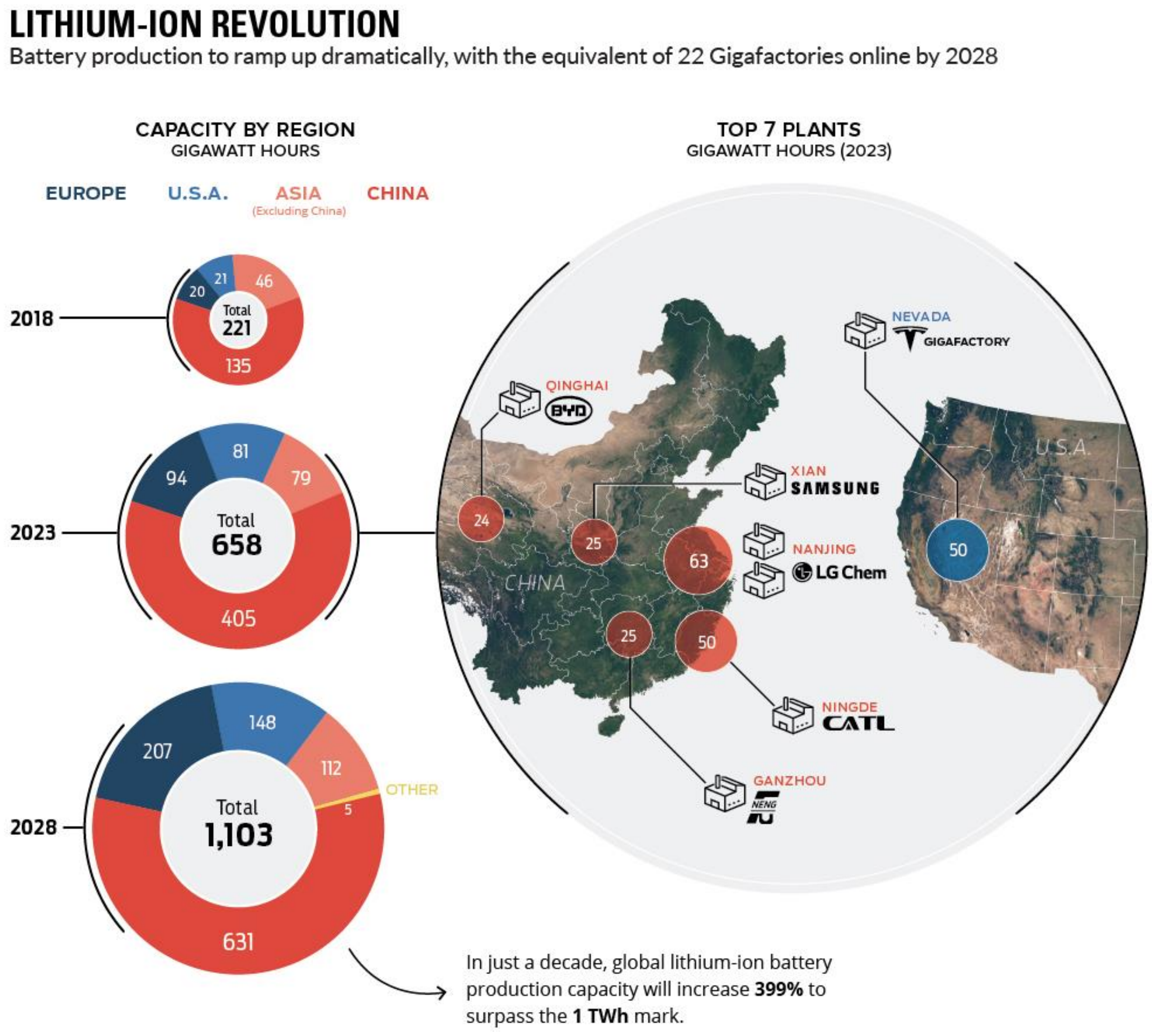


Figure 30: Gigafactories worldwide [73].

There is a large motivation within the EU and European countries to ensure that a greater part of the battery value chain remains in Europe. This is both due to raw material supply issues, as well as the need to shorten the distance between European car manufacturers and battery cell manufacturers. Thus, there are quite a few gigafactories for battery production in Europe that is under planning or construction over the next years. A description can be seen in Figure 31 and Figure 32. There is a mix between Asian manufacturers setting up new plants in Europe, and fully owned European initiatives setting themselves up, such as Northvolt (expected to deliver 32 GWh by 2023).

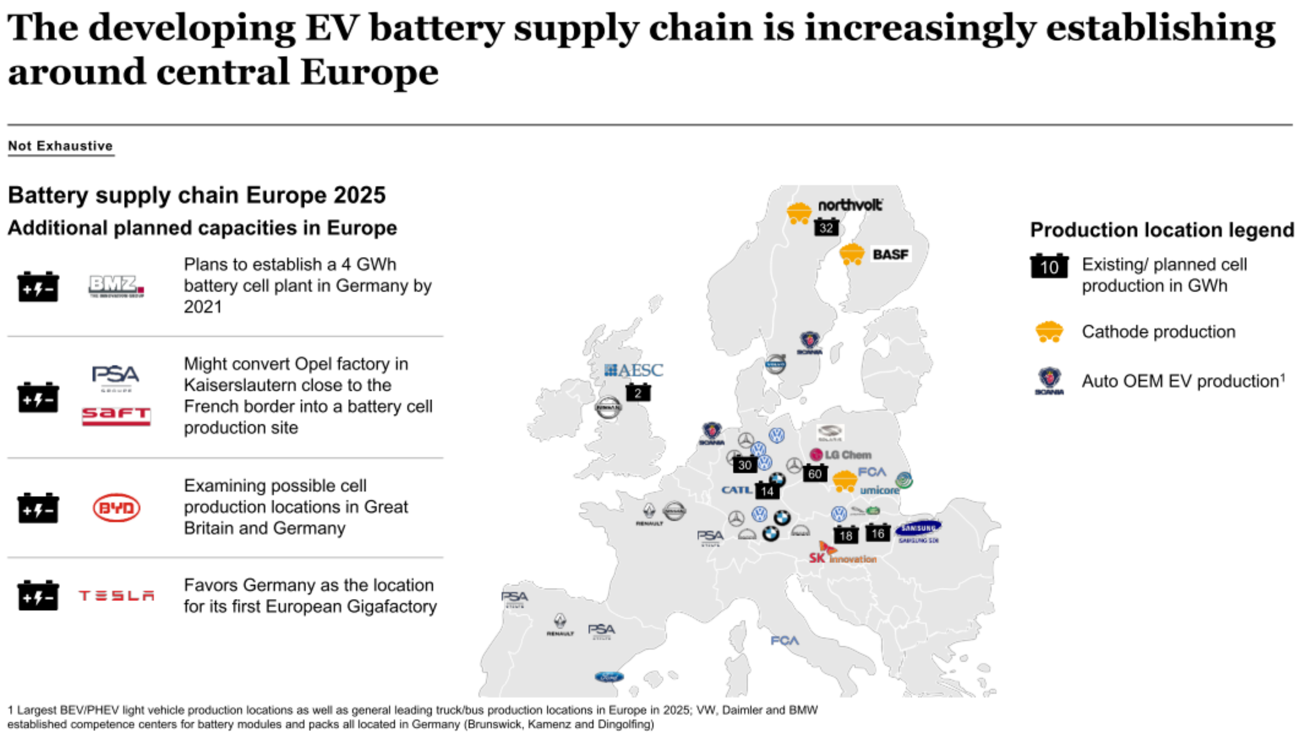


Figure 31: Planned battery factories in Europe [74]. *Source: McKinsey.*

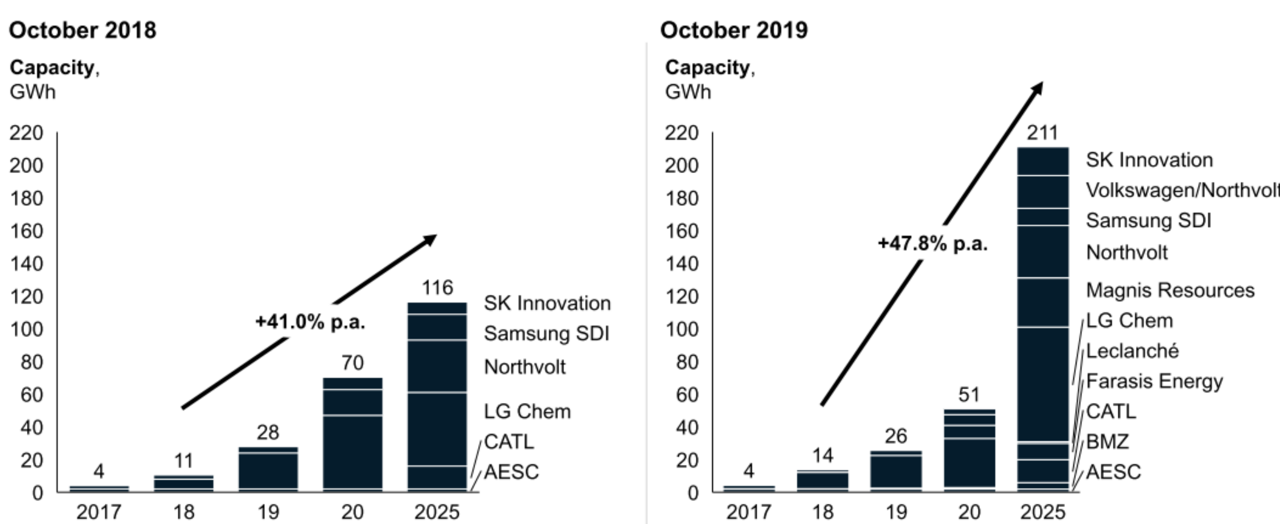


Figure 32: New plans for cell manufacturing plants in Europe October 2018 vs. 2019 [74]. *Source: McKinsey.*

There are also reports that Volkswagen, Saft and Tesla are setting up new factories in Europe [75]. In addition, Freyr is planning a battery production facility in Mo i Rana, Norway, which is also planned to deliver 32 GWh in 2023. As the forecasts for 2030 predicts, all these gigafactories (and more) will be needed to meet the future demands, and the greatest obstacle is currently funding of such large projects and not losing innovative edge over established sites in Asia.

The various battery producers are known for different battery chemistries, but the overall trend goes towards a larger fraction of NMC, with a lower Co-amount due to increased prices of Co (and reduced availability). Both LG Chem and SK Innovation have said they are working on producing NMC-811-type batteries, which will probably become predominant once they hit the market with full force [76]. China's largest battery producer CATL is currently making NMC-523 but has a roadmap that will begin production of NMC-811 in 2019. CATL has an ongoing strategic agreement with both BMW and Volkswagen, and started construction of its first European plant in Germany in the fall of 2019, which will surely place these batteries in European made cars [77].

The battery chemistry to be used at the Northvolt site is expected to be NMC-based, and the battery producer will also establish an R&D section to continue the development of the optimal battery chemistry [78]. Northvolt is also teaming up with BMW and Umicore to establish a closed-loop life-cycle in Europe for EV batteries [79][80]. The Norwegian initiative Freyr has no stated preferred chemistry, but like Northvolt the company will focus on "green" production of battery cells, aiming to provide the market with new Li-ion battery cells with an extremely low carbon footprint.

The Tesla Gigafactory producing Panasonic batteries still focuses on the NCA chemistry, where they claim to have reduced the Co-amount to lower than what would be found in NMC-811 [81]. Later patents from Tesla state that they are also involved in NMC chemistries [82].

2.7. Future cell chemistries and technologies

In research, there is a lot of effort being put into the development of future chemistries beyond Li-ion. It is assumed that time-to-market from a research lab is between 10 and 20 years [83]. The technology evolution is often divided into generations. Table 11 and Figure 33 sum up what is mapped out for the foreseeable future: we are currently in generation 2b but see more and more of generation 3a. Some of the most promising technologies with variable time-scales for introduction into the market include Li-metal, Solid State, Li-Sulphur, Li-air and Na-ion batteries. These will be elaborated on below, based on reports found in [2] and [40]. Supercapacitors are another technology hitting the market, and even though they will not replace Li-ion batteries as we know, they can enable new combinations of possibilities regarding power and acceleration, more on this towards the end of this section.

Table 11: Generations of Li-ion battery technology. Generation 2b is the current state-of-the art. Table adapted from [84].

		Assumed time-frame	Cathode	Anode
Li-ion	Generation 1	2015	NFP, NCA	100% graphite
	Generation 2a	2015	NMC 111	100% graphite
	Generation 2b	2017	NMC523 to 622	100% graphite
Optimized Li-ion	Generation 3a	2020	NMC622 to 811	Graphite + Si (5-10%)
	Generation 3b	2025	HE-NCM, high voltage spinel	Si + graphite
New generation	Generation 4	> 2025	Conversion materials (sulfur) [All-solid-state]	Li-metal
	Generation 5	2030	Air	Li-metal

The EU-calls (Horizon 2020/Horizon Europe [85]) that are available in 2019/2020 target mostly generation 3b (and further) to enable the European industry to develop relevant battery technology for EVs and stationary storage. The higher the technology-readiness-level (TRL) level is required, the lower generation is targeted in the calls. Figure 33 illustrates the gravimetric vs. volumetric energy density of the various battery technology generations.

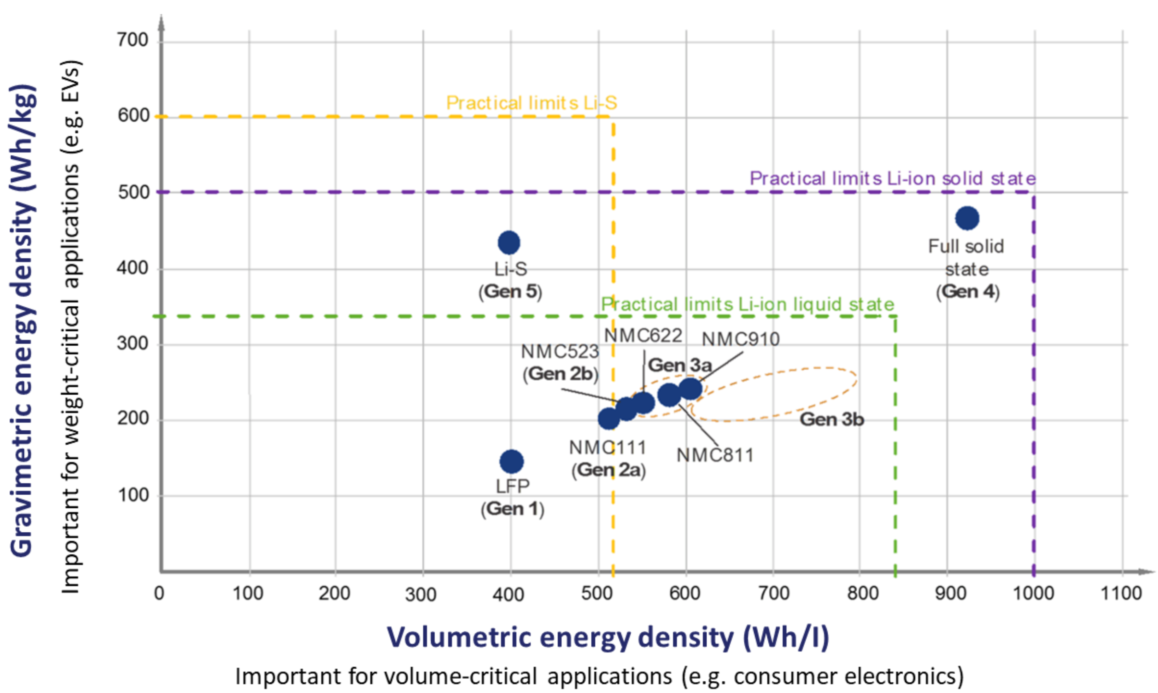


Figure 33: Characteristics and market potential of Li-ion technologies. From EMIRI Roadmap 2019 [27].

Lithium metal batteries (Li-metal)

Li-metal was early on an interesting anode material, as it ideally can store Li^+-ions quite well. Naturally, its capacity would significantly exceed that of graphite used in batteries today. However, parasitic reactions of Li metal with liquid electrolytes, unstable and dendritic electrodeposition leading to dendrite-induced short circuiting, led research to believe it was not possible to commercialize. However, recent efforts to minimize these reactions by introducing artificial SEI-designs, hybrid layered electrolytes or solid-state electrolytes have brought Li-metal back on the table again.

Solid State batteries (SSB)

Solid State batteries (SSB) use solid electrolytes that have been covered earlier (see Section 2.3.2). The interest into SSBs is largely due to safety concerns with liquid electrolytes, as inorganic solid electrolytes are much more stable at higher temperatures. Since they are more mechanically rigid, they will also help aid the use of Li-metal anodes. Researchers still face many challenges related to manufacturing and fundamental understanding of the materials. Specifically, Li-ion conductivity is still too low at room temperature, and even at EV-relevant temperatures of 80 °C the rate capability is limited (limiting fast charging).

Lithium-sulphur batteries (Li-S)

Li-S batteries are considered a very promising future technology for EVs, where high-capacity sulphur cathodes combined with Li-anodes would give a cheap high-energy-density system. However, S has low electrical conductivity and the cathode experiences large volume changes upon cycling requiring some way to passivate the interfaces to inhibit dendrite formation. The toxic impacts of a Li-S battery would be lower than conventional Li-ion by avoiding Ni and Co (NMC), mostly due to mining and production issues. However, when considering a wider range of environmental impacts, production of S-cathodes may have higher emissions and more energy intensive production processes.

Lithium-air batteries (Li-air)

Li-air is probably the holy-grail of Li-ion technology, and it is quite far from commercialization. It combines two challenging electrodes, Li-metal and air, and there is a lack of true understanding of the fundamental chemistry behind. Also, the air would require filtration units or oxygen tanks to improve the purity of the oxygen and avoid degradation in ambient air. However, if realized it would give a battery with higher theoretical specific energy density known, 3,500 Wh/kg and facilitate driving ranges exceeding 500 km. Practically, oxygen tanks and filtration units are energy-intensive and will greatly reduce the effective energy density.

Sodium ion (Na-ion)

This technology moves completely away from Li-ion, and in its place utilizes Na-ions which are abundant and with no geopolitical resource issues. Even though it is less energy dense than Li, it has great potential especially in stationary storage units where weight and volume are less critical than for EVs.

Supercapacitors (SC)

Supercapacitors are an energy storage technology that is related to and sometimes found working along with battery technology. Supercapacitors rely on high surface area materials and are characterized by the ability to store and release energy at rates that are much greater than what can typically be achieved by batteries. However, because they only store charge in the surface or near surface of the electrodes, their capacity is comparatively less than that of typical batteries. With little to no chemical or structural change to the electrode, supercapacitors can have significantly longer cycle life in the hundreds of thousands or millions of cycles. Thus, supercapacitors often find applications in high power use cases like camera flash in consumer electronics or regenerative braking in hybrid electric vehicles alongside battery systems for longer-term portable energy usability.

Supercapacitors can be categorized as electric double-layer capacitors (EDLC), pseudocapacitors, or hybrid supercapacitors according to whether the respective working principle of energy storage is electrostatic Helmholtz double-layer formation, electrochemical redox, or a hybrid of the two. In general, EDLCs typically use activated carbon for its low cost, high stability, and extremely high surface area while pseudocapacitors use transition metal oxides or in high-performance instances, platinum group metal oxides like ruthenium or iridium oxide [86]. Activated carbon can be produced from a wide range of carbon sources, including agricultural waste materials, although fossil fuel-based hydrocarbons tend to yield the best performing materials. A wide array of materials is available for use in hybrid supercapacitors, especially Li-ion capacitors that can utilize high surface area versions of optimized battery electrode materials.

The market size of EDLCs is estimated at $980 million USD [87]. The global EDLC market has been forecasted to grow at a CAGR of 9.37% from 2017 to 2021 [88]. However, future forecasts in 2019 project a CAGR of 16.5%, growing the market to $3.31 billion USD in 2025 [87]. The EDLC market is primarily dominated by a few firms in Japan and the US. In Japan, Panasonic, NEC Tokin, and Nippon Chemi-Con Corp are the established players. In the US, Maxwell Technologies (acquired by Tesla in 2019) is the most well-known. For Li-ion (hybrid) capacitors, Fujikura, JM Energy Corporation and Taiyo Yuden are major developed firms from Japan while Maxwell Technologies is again the main mature manufacturer in the US, although many startups targeting Li-ion capacitors have arrived in recent years [89]. Within Europe, Skeleton Technologies in Estonia manufactures supercapacitors and Maxwell Technologies has European offices, but there are no producers in Norway except for startup companies such as Beyonder.

3. Segments

In this section data and forecasts are combined to compare different segments while more information on the specific chemistries referred to can be found in Section 2.2.1. The main segments in this report include: Personal vehicles (PVs), public transport vehicles (buses), commercial vehicles (light and heavy-duty trucks), shipping and ferries. Some information (where it was available) is also included on stationary storage units and small niche markets, but this is not the focus of the report. An overview of the different LIB technologies and their main applications can be seen in Figure 34.

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

Figure 34: Li-ion battery technologies, performance and main applications [27].

There are several degrees of electrification for EVs, and an overview is given below [11]. If no specification is given, the vehicles may be characterized as an xEV, where x refers to the specification of the EV.

Hybrid Electric vehicles (HEV)
Battery is only charged during braking when driving using the internal combustion (IC) engine.

- Micro-hybrid: The vehicle's IC engine turns off when idling, and instantly starts again when moving. This type of vehicle offers little to no electric power to move the vehicle.
- Mild hybrid: Includes start-stop capability, and small electric motors with slightly larger batteries providing boost during acceleration leading to some engine downsizing.
- Full hybrid: Including the benefits of the former systems, this vehicle has a large enough electric motor and battery to be able to move the vehicle on its own for a short distance.

Plug-in Hybrid Vehicle (PHEV)
Similar to hybrids, but able to move the vehicle an extended distance (i.e. 10-50 miles) on electric power due to a larger battery that can be charged via an external plug.

Full Electric Vehicle (EV)[1]
The 100% battery-driven vehicle reliant on charging using an external plug.

A recent presentation by Avicenne in January 2019 shows the numbers for EVs sold world-wide [24] (cf. Figure 35 and Figure 36). From year 2000 the Li-ion market has gone from being dominated by portable electronics, to 66% of the market in EVs (Figure 38), where the largest growth is in China due to high incentives.

The MWh-needs for the different segments (also split into HEV, PHEV and EV) are presented in Figure 37, adding up to a forecasted need of > 1 TWh [24] in 2030. Forecasts by Bloomberg go even higher, estimating the demand of 1 TWh already just after 2023, see data in Figure 38.

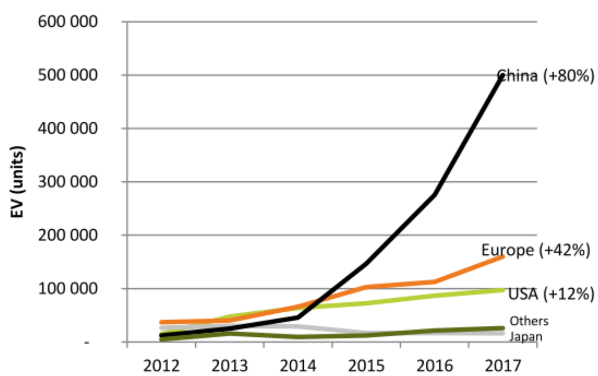


Figure 35: >800 000 EVs sold worldwide [24].

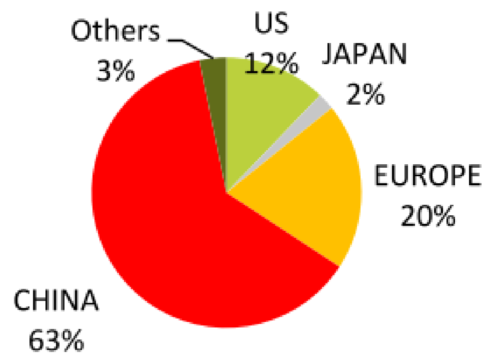


Figure 36: EVs sold per region [24].

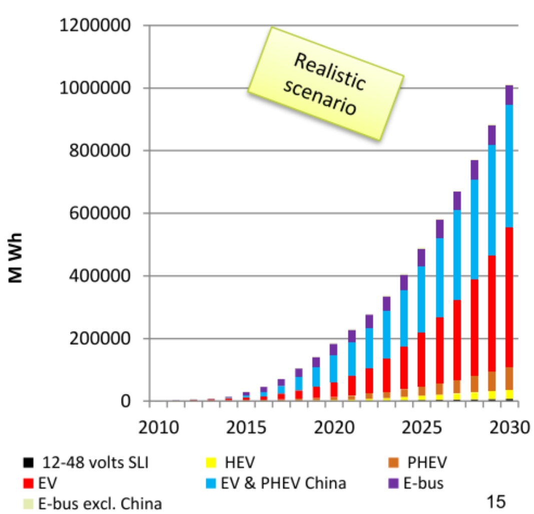


Figure 37: Li-ion needs in MWh, forecasted for all segments [24].

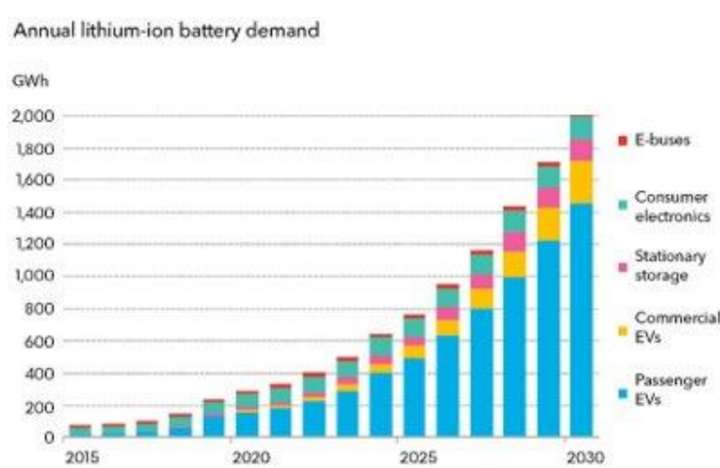


Figure 38: Annual Li-ion battery demand, split into segments. [4]

[1] Sometimes the full-electric vehicles are referred to as battery electric vehicles (BEV), but in this report EV will be used for this classification.

Bloomberg also estimates the the EV share of total sales as well as the share of the fleet per segment (see Figure 39), both of which is expected to increase significantly over the next decades. As shown, the e-bus share is quite high, again, due to early subsidies in China.

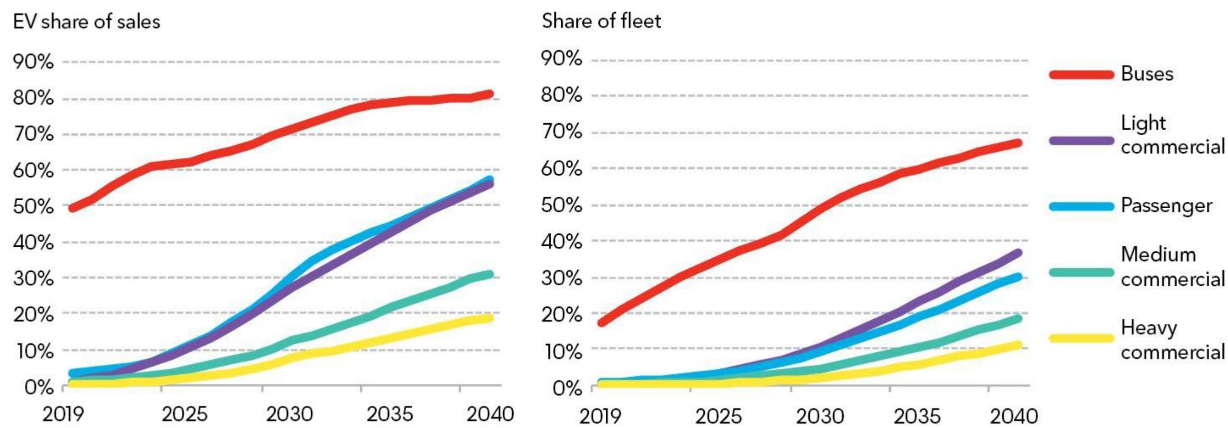


Figure 39: EV share of the sales (left) and of the global vehicle fleet (right) per segment [90].

The development of different EV outlooks (including personal and commercial EVs) is presented in Figure 40. In general, trends seem to be adjusted to higher growth rates i.e. there has been a general tendency in underestimating the growth of the EV fleet [91].

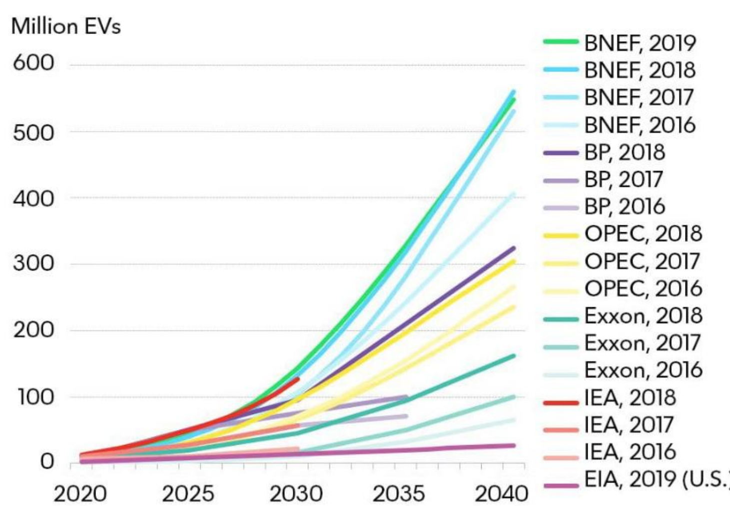


Figure 40: Comparison of different EV outlooks then and now [91].

3.1. Personal vehicles

3.1.1. Status today

Currently, there are four major lithium-ion battery chemistries being used in the xEV sector: NMC, NCA, LMO and LFP each having different characteristics and thus different advantages and disadvantages.[1] Some manufacturers also produce cathodes with a mix of NMC for range and

[1] Besides Li-ion batteries, NiMH batteries were used in previous-generation xEVs and remain in use for some HEVs. Newer generation EVs and PHEVs use almost exclusively Li-ion batteries.

LMO (up to 30% [92]) for acceleration (e.g. Nissan Leaf). Besides the technical specifications, the content of critical raw materials (CRM) differs widely amongst the different battery types.

Depending on the type and size of the car model, they have increasingly large battery packs. Small models have around 12-18 kWh, mid-sized 22-32 kWh and luxury models typically have batteries 60-100 kWh [93]. These numbers are continuously increasing as manufacturers introduce better and better batteries into their models. Globally, the xEV vehicle sales make up about 4% of car sales in 2019, with almost half of this being in China [94]. In Norway however the share is 46%, and is compared to China, Europe and other relevant countries in Figure 41 and Figure 42.

Figure 41: Electrical vehicle market update. Note: EV sales include BEV and PEV. EV penetration rate refers to five main regions (China, Japan, South Korea, Europe, North America). China data excludes low-speed EV sales and commercial vehicles. BloombergNEF [94].

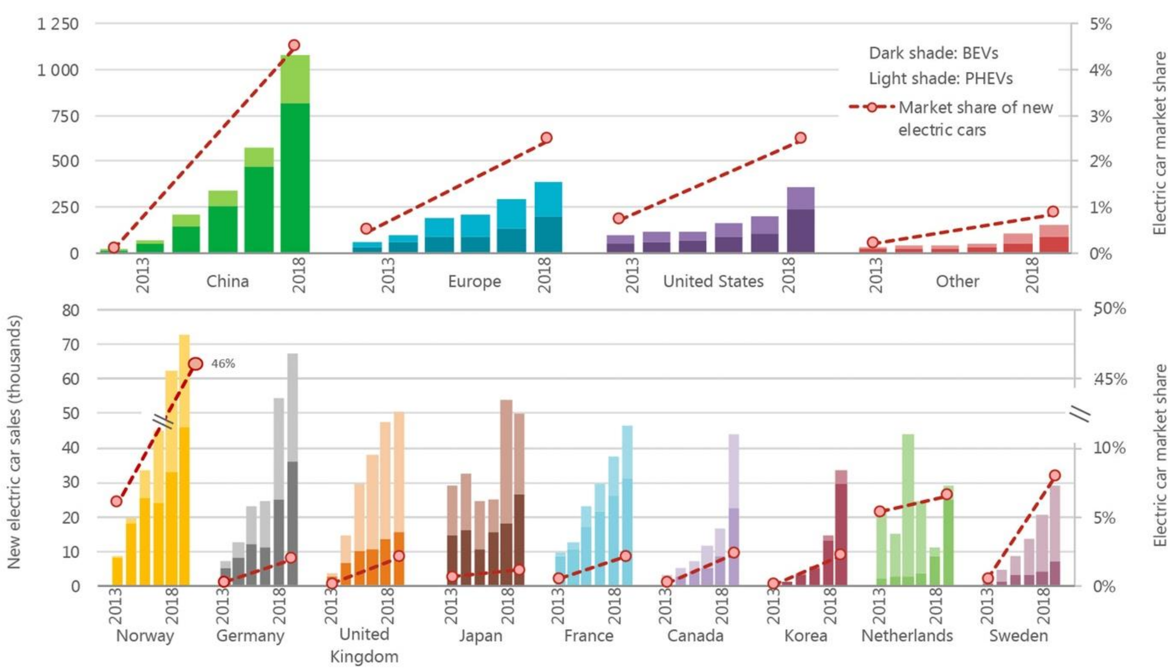


Figure 42: Global electric car sales and market share, 2013-2018. IEA Global EV outlook 2019 [95]

3.1.2. Manufacturers and market outlook

The following forecast is based on the latest EV market report by Avicenne from January 2019, comparing HEVs, PHEVs and EVs [24]. It clearly shows a large growth in all types of personal vehicles, but the largest share is seen for HEV with an assumed 28.8 million sold cars in 2030.

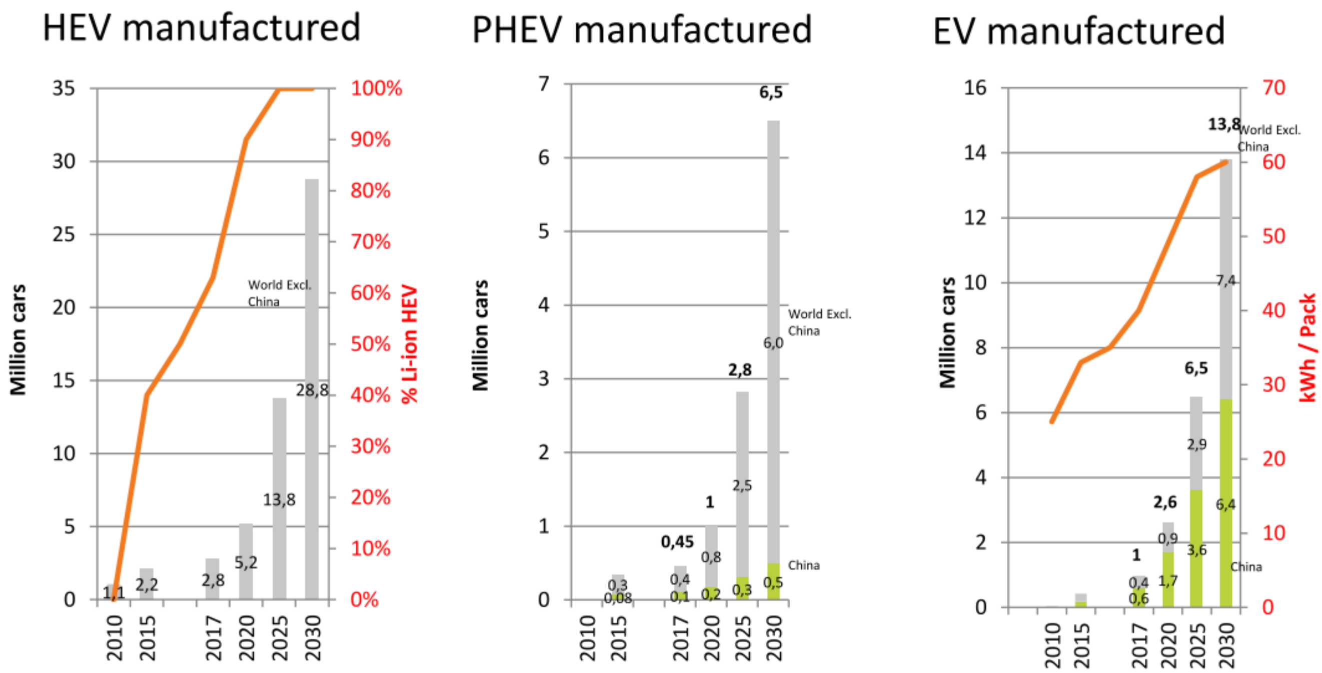


Figure 43: Manufactured and forecasted growth for xEVs world-wide and in China (green). Assumptions: HEV 1kWh/car, PHEV 12 kWh/car [83].

3.1.3. Material needs and compositions

We saw in Section 2.2.3 that the largest change in material needs comes from the huge expected growth of high-Ni NMC cathodes. NMC cathodes are moving from being 111, to 622 and further into 811 compositions leading to a 24-fold increase in Ni-demands just for the cathode chemistry alone. This is also reflected in the following table:

Table 12: Expected market shares of Li-ion chemistries for EV, HEV and PHEV applications in 2020 and 2025 versus 2015 [96].

	NMC (%)	NCA (%)	LMO (%)	LFP (%)
2015	25	18	45	12
2020	30	18	26	26
2025	28	23	17	32

3.1.4. Related issues

As we have seen, Ni is a plentiful resource and reducing Co and increasing Ni is a good shift for the battery market overall. However, it is a well-known problem that charging infrastructure is the limiting factor for many to move from gasoline-driven cars to xEVs as range anxiety is well established among users. Expanding this infrastructure requires a large amount of raw materials like Cu and Al as well as class-2 Ni as we saw earlier. According to reserves of Ni, Cu, and Al the global material capacity is large enough, but the production capacity is behind in all areas of mining.

3.2. Public transport vehicles

3.2.1. Status today

On a world-scale, 98% of all electric buses are in China, but the numbers of electric buses operating in Europe has been continuously increasing in the last couple of years (see Figure 44). As of today, around 4,000 electric buses are running in Europe (including electric, PHEV, trolleybus, in-motion charging bus (IMC) and fuel cell buses). It is assumed that the share of electric city buses sold in Europe will surpass 10% by the end of 2019 and increase to 20% in 2020 [97]. The development of the number of electric buses in the EU is illustrated in Figure 44. The numbers of electric buses by the end of 2019 in the Nordic countries are shown in Figure 45. There was a tremendous increase in numbers, from 56 electric buses in 2018 to 467 buses in 2019. The forecasted share of total sales as well as the share of the fleet between 2019 and 2040 was shown in Figure 39.

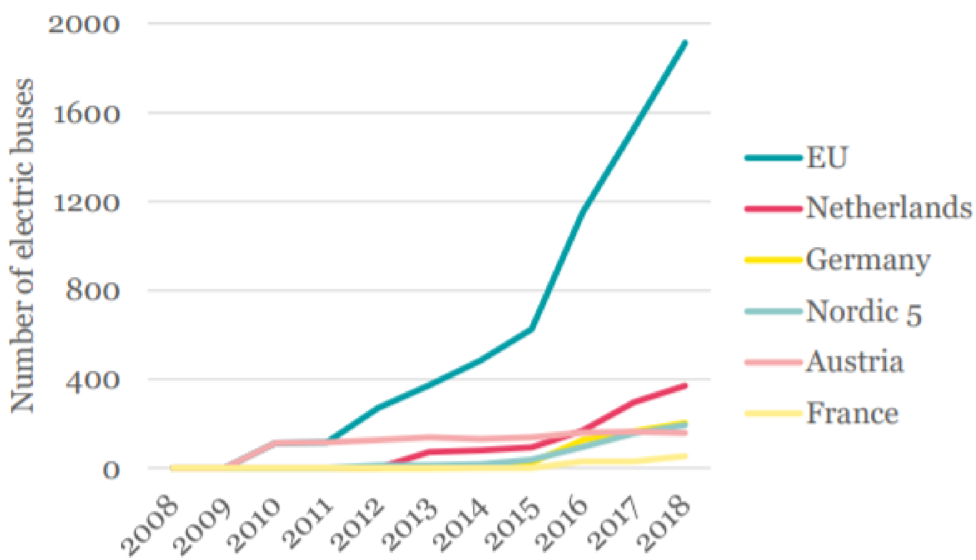


Figure 44: Number of electric buses operating in the EU [98].

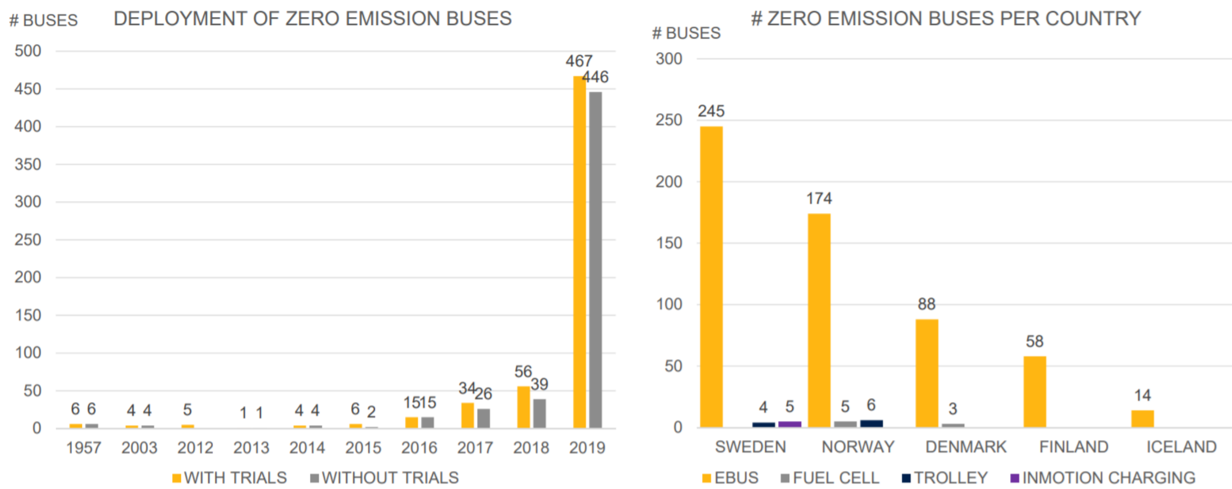


Figure 45: Deployment of zero emission buses in the Nordic countries by the end of 2019 [99].

Following this trend, Norway is also seeing an increasing use of electric buses, and almost monthly, new additions to the current fleet are announced. A summary of the development of the electric bus fleet in Oslo and Romerike by Ruter (including manufacturers and battery type) is presented in Table 13. In 2019 Ruter has a total fleet of 115 battery-electric buses.

Table 13: Development of the electric bus fleet in Oslo and Romerike [98].

Project/ tender	Qty	Mfg	Bus type	Charging concept	Chg power (kW)	Battery capacity (kWh)	Battery type	Contains cobalt
Test 2017	2	Solaris	solo	Pantograph	300	75	LTO	No
Test 2017	2	Solaris	solo	Pantograph	400	125	LTO	No
Test 2017	2	BYD	articulated	Plugin	80	307	LFP	No
Oslo 2019	30	VDL	articulated	Pantograph	300	170	LTO	No
Oslo 2019	10	VDL	solo	Pantograph	300	127	LTO	No
Oslo 2019	20	BYD	articulated	Pantograph	300	348	LFP	No
Oslo 2019	4	Solaris	solo	Pantograph	400	146	LTO	No
Oslo 2019	6	Mercedes	solo	Pantograph	250	243	NMC	Yes
Romerike 2019	17	Volvo	solo (w/seat belts)	Plugin	150	200	NMC	Yes
Romerike 2019	22	BYD	articulated (belts)	Pantograph	300	348	LFP	No

In addition to that, Unibuss has recently ordered another 23 electric busses from the Chinese manufacturer BYD (expected delivery Q2 2020) for operation on routes in and around Oslo, and 55 BYD electric busses have been ordered by Vy buss in November 2019 [100]. There is also a plan to add 41 buses in "Vestkontrakten" [101]. In Trondheim, 36 new e-buses from Heuliez and Volvo were deployed in August 2019 with battery packs of 90-150 kWh depending on route and type of battery used [102]. In Bergen, 80 new e-buses are to be deployed in 2020 [102].

3.2.2. Manufacturers and market outlook

The largest electric bus manufacturers are obviously located in China. One of the largest Chinese manufacturers, BYD, is also starting to take up a significant market share in Europe: BYD currently has over 1000 busses in operation across Europe. All of them employ LFP batteries, the newer ones include BYD's latest BTMS (Battery Thermal Management System) technology.

Most of the 467 e-buses in the Nordic countries are manufactured by BYD, VDL and Volvo (see Figure 46).

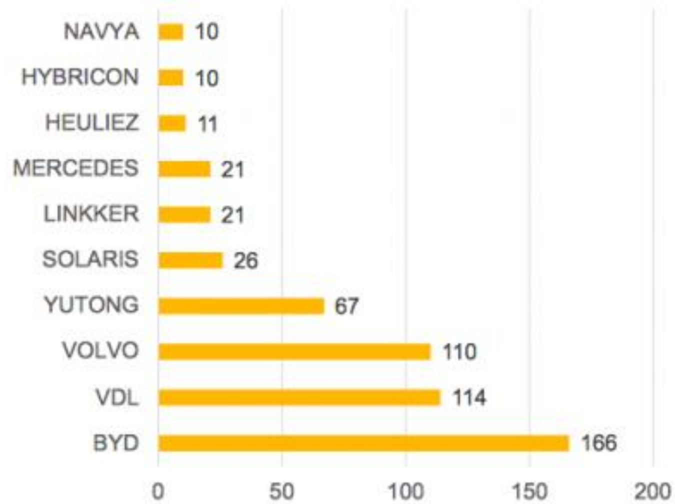


Figure 46: Manufacturers with most zero emission buses in the Nordic countries [99].

The polish manufacturer Solaris is also growing quickly, accounting for 25% of all contracts landed for electric busses in 2019. Volvo Buses[1] is the first manufacturer to stop the production of diesel buses for the European market and is fully rolling out electric alternatives. At Busworld Europe 2019 a new model (Volvo 7900 Electric Articulated) was released, with a capacity that can reach up to 396 kWh. Mercedes, MAN and Iveco announced in summer of 2018 that their production of electric buses would start in 2019/2020. Mercedes launched their first model (eCitaro) which started production at the end of 2018, with a second-generation model expected for 2020 (330 kWh, up to 250 km). MAN presented their first electric model (Lion's City E) also at IAA in 2018, with mass production assumed in 2020. Its battery size is expected to be 480 kWh for a solobus, and 640 kWh for the articulated version. These are huge in comparison to others on the market and could ensure 200 km range in realistic conditions [97].

Manufacturers of Ruter's electric buses in Oslo are included in Table 13. An overview of bus manufacturers including e-bus-projects listed by cities in the EU was published as part of the ZeEUS[2] project end of 2018 and can be found in the corresponding reference [103].

[1] There are speculations that Akasol supplies batteries to Volvo and Mercedes: https://www.sustainable-bus.com/news/batteries-for-commercial-vehicles-big-follow-up-order-for-akasol/

[2] Zero Emission Urban Bus System https://zeeus.eu/

3.2.3. Material needs and compositions

Currently, LFP is the dominating cathode material in the public transport segment due to the large market share of China. Figure 47 illustrates the electric bus sales by cathode material for China and on a global scale excluding China. In China, about 95% is LFP. This can be attributed to the cheaper production costs, increased safety as well as the lower requirements on battery density and available subsidies [104]. NCA/NMC plays a more important role in the market outside of China and is predicted to take up an even larger share in the near future.

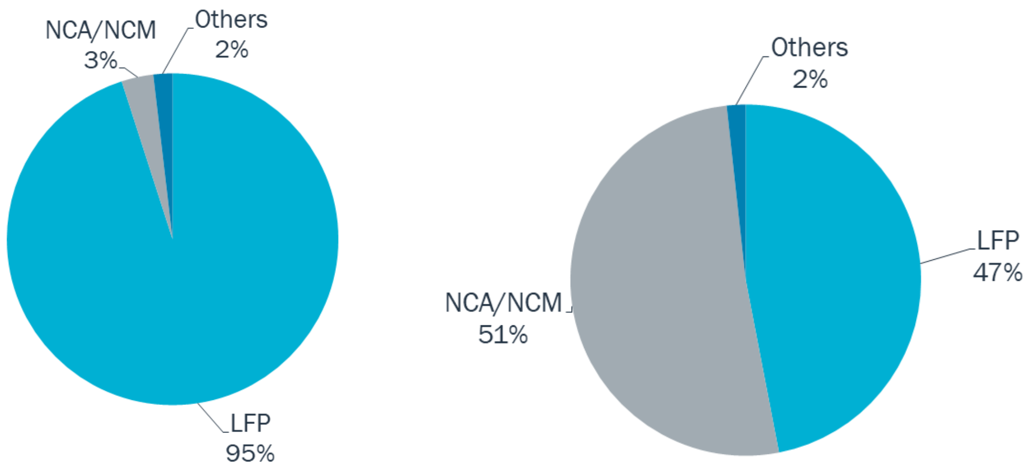


Figure 47: Electric bus Li-ion battery sales by cathode material. Left: China. Right: Global, excluding China [104].

Figure 48 summarizes the worldwide market shares in 2018 and the expected development until 2028: On the long-term, an overall increase in NMC is foreseen, taking up about 42% of the total market, while LFP is going down to about 58% by 2028 according to IDTechEx [105]. This is mainly because the capacity of LFP batteries in electric buses is limited to about 400 kWh, while NMC-type batteries are reported to allow for a capacity of up to 818 kWh [104]. No details on what type of NMC in use are available, but we expect an increase in Ni-content, following the trend in the personal vehicle sector.

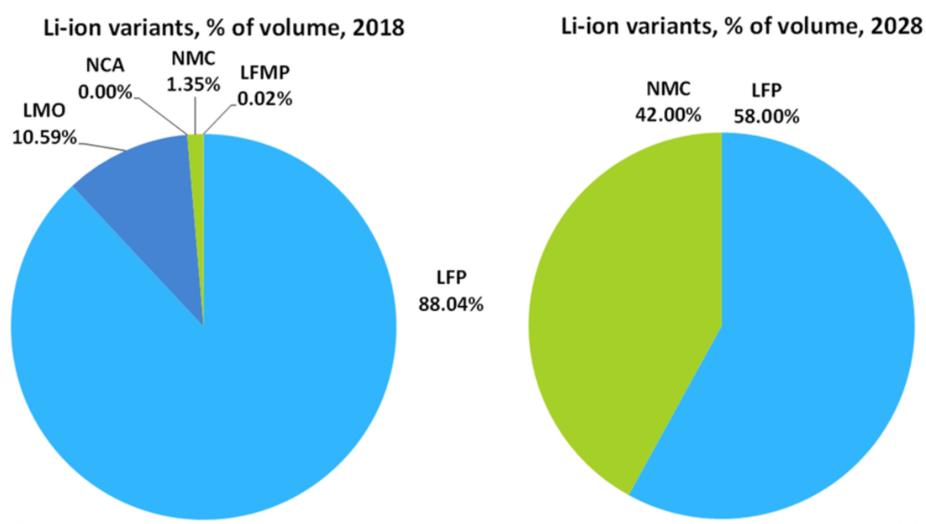


Figure 48: The battery market of lithium-ion variants by % sales volume for electric buses (hybrid and pure electric buses) [106].

Owing to the requirement of fast recharge, LTO seems to play an increasingly important role as an anode material in batteries for electric buses (see also battery type in Table 13 and ZeEUS report [103]). No actual numbers on the market share of LTO as an anode material are currently available, but it can be assumed that the use of LTO as an anode depends on the employed charging strategy (e.g. opportunity vs depot illustrated in Figure 49). One example of making use of the fast-charging capability of LTO batteries is the TOSA (Trolleybus Optimisation Système Alimentation) concept that has been in operation in Geneva and Nantes for more than one year allowing for flash-charging along the route [107].

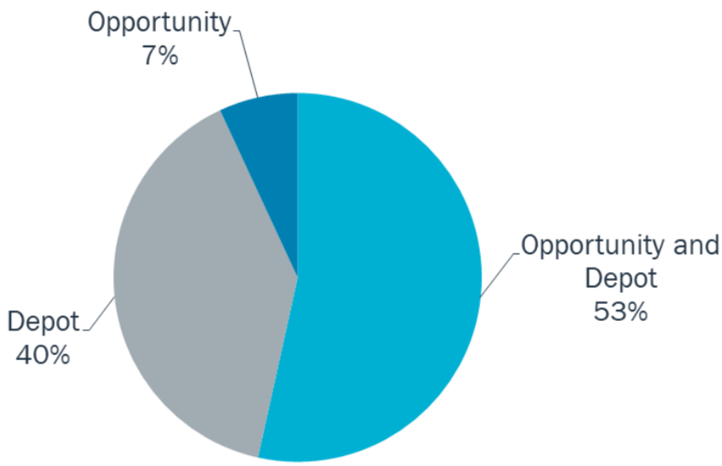


Figure 49: Europe installed base electric bus charging infrastructure 2018 (Source: Interact Analysis) [104].

Other rather niche battery types that are currently used are e.g. the Sodium-Nickel-Chloride battery (also SoNick or ZEBRA battery), mostly developed by Fiamm and General Electric, as well as Li-Metal-Polymer batteries developed by Blue Solutions [108].

3.3. Commercial vehicles[1]

3.3.1. Status today

Number of electric heavy trucks operating in the EU started to increase in 2012 with the deployment of electric trucks in the Netherlands and has been increasing ever since (see Figure 50). Most electric trucks that have been introduced are medium freight trucks (gross vehicle weight of 3.5-15 tons) operating in cities or suburban areas. Electric heavy freight trucks (> 15 tons) have mostly been developed for pilot projects, but their numbers are also on the increase.

[1] More on this segment can be found in the following book: “Electric trucks: a history of delivery vehicles, semis, forklifts and others.“ [148]

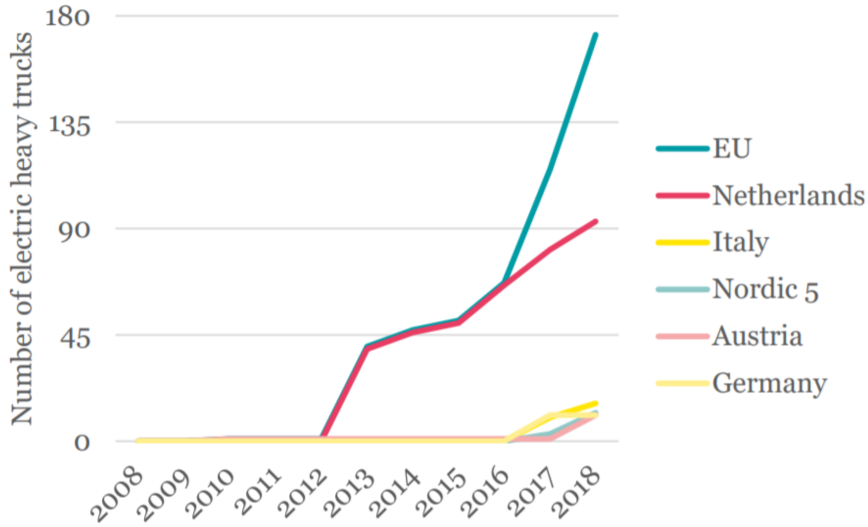


Figure 50: Number of electric heavy trucks operating in the EU [98].

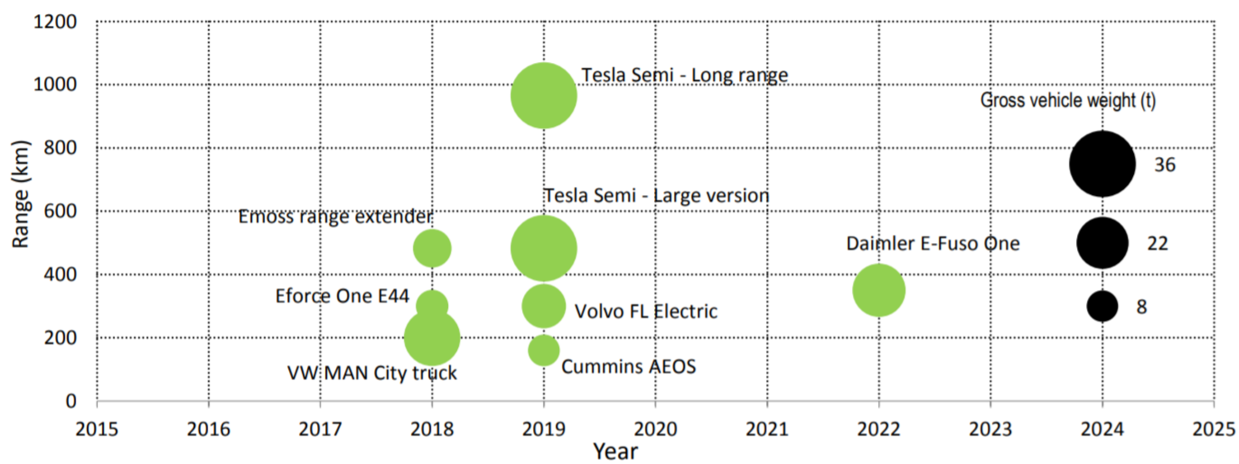


Figure 51: Heavy duty electric truck models (> 15 tonnes) announced for commercialization [109].

The number of electric trucks registered in Norway saw a significant increase from only one registered truck in 2017 to 13 in 2018 (see Figure 52) and is expected to keep increasing, similar to the number of all electric vans and small trucks (Figure 53). Already in 2018, 11.7% of vans sold in Oslo were electric [110]. According to the Norwegian National Transport Plan, by 2030 all new heavy vans, 75% of new long-distance buses and 50% of new lorries in Norway are to be zero-emission vehicles [111]. Goldstein Research analysts forecast that the Norwegian electric trucks market is expected to grow at a CAGR of +45% between 2017 and 2025 [111].

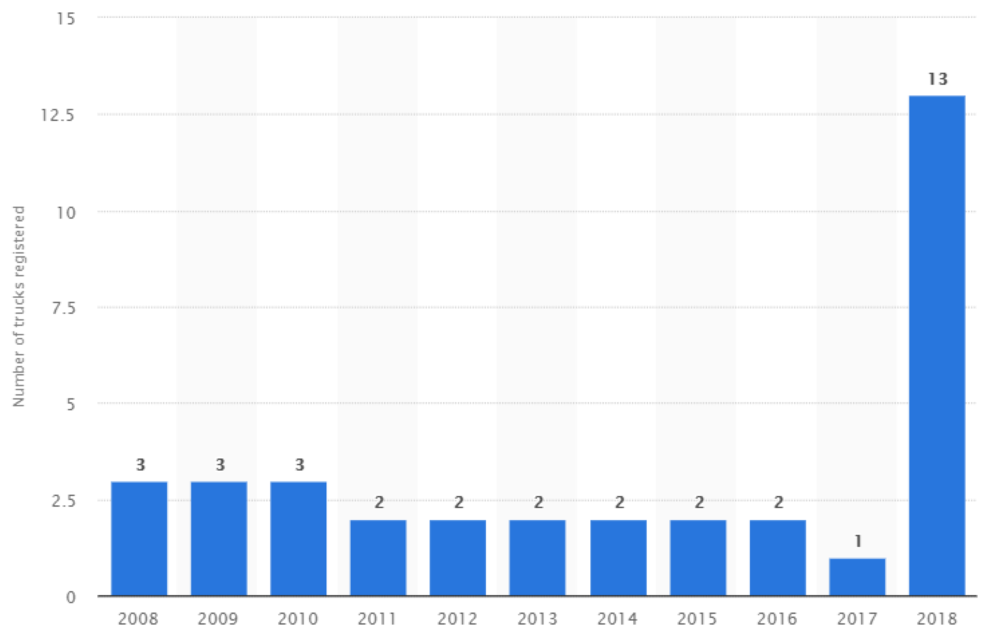


Figure 52: Number of electric trucks registered in Norway [112].

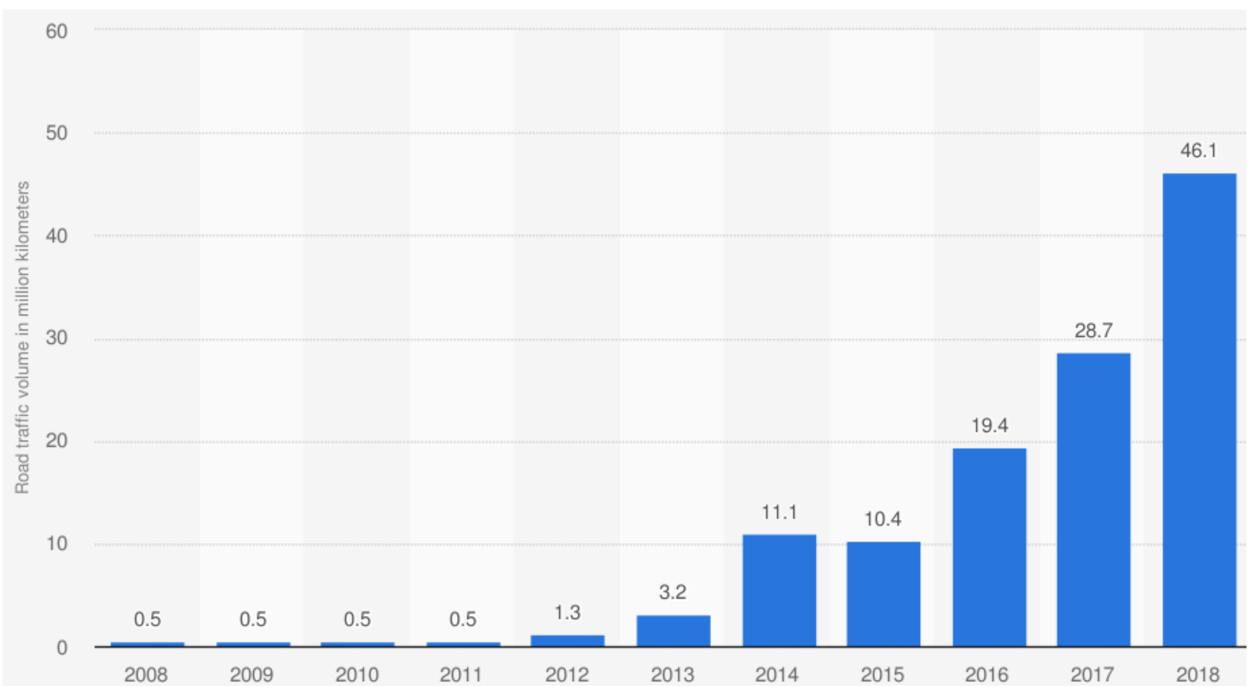


Figure 53: Road traffic volume of all electric vans and small trucks in Norway from 2008 to 2018 (in million kilometers) [113].

A summary of some electric heavy-duty vehicles in Norway is given in Table 14. These have mainly been in use for waste collection. E.g. the first electric waste collection truck in Oslo was introduced by the waste and recycling company Ragn-Sells in summer 2017 and they announced that they are about to introduce more electric vehicles in their business (i.e. electric tractors and excavators) [114]. The food delivery company ASKO was the first to procure a fully electric truck (EMOSS, 240 kWh battery pack), and 10 tesla trucks have been ordered [115][116].

In addition to electric trucks in the waste and transport sector, there is a trend towards Zero Emission Construction Sites: e.g. the upgrade of Olav Vs gate in Oslo is the first zero-emission construction site in the world, requiring that every excavator, wheeled loader and other equipment to be electric [117]. According to DNV GL it is likely that all types of construction machinery may be electrified by 2030.

In summary it can be said that a growing number of electric commercial vehicles become available on the market, offering a large variety in sizes and ranges [118]. According to the New Policies Scenario, the world's stock of electric trucks will reach close to 1 million in 2030, the EV30@30 even predicts 2.5 million. However, these scenarios still show low shares of electric trucks among the total truck fleet (1% and 3% respectively), due to the challenging requirements on truck operations (i.e. freight weight and long distances) [109]. The forecasted share of total sales as well as the share of the fleet between 2019 and 2040 (split up into light, medium and heavy commercial vehicles) by BloombergNEF was shown in Figure 39.

Table 14: Selected heavy-duty electric trucks in the south of Norway starting operation around 2017/2018 [119].

	Nor Tekstil	BIR	Renovasjonen	ASKO	Norsk Gjenvinning	Ragn-Sells	Stena Recycling***
Sector	Manufacturing	Waste collection	Waste collection	Freight transport	Waste collection	Waste collection	Recycling
Vehicle type	Heavy van	Truck (waste)	Truck (waste)	Truck (freight)	Truck (waste)	Truck (waste)	Tractor (recycling)
Manufacturer	Iveco	DAF/Emoss/ Geesinknorba	DAF/Emoss/ Geesinknorba	MAN/Emoss	Dennis Eagle/PVI (Renault)	MAN/Emoss/ Allison	MAN/ Emoss/ Allison
Expected driving range (km/y)	30 000	20-26 000**	16 800**	50 000*	18 000****	80 000**	120-130 000
Range on full charge (km)	160	120-130	100-140	180	140	200	178
Number of vehicles tested	5	1	1	1	2	1(+1)	2
Registration year	2018	2018	2018	2016	2018	2018(2019)	2018
Total weight (t)	5.6	12.0	12.0	18.6	26.8	28.0 (50.0)	40.0-45.0
Payload (t)	2.6	3.5	3.5	5.5	9.7	18-19	15-20
Length (m)	7.2	7.0	7.0	9.0	9.5	7.8	7.4
Battery technology	Sodium nickel chloride ($Na\text{-}NiCl_2$)	Lithium-ion (LIB)	Lithium-ion (LIB)	Lithium-ion (LIB)	Lithium-ion (LIB)		Lithium-ion (LIB)
Battery capacity (kWh)	80	120	130	240	240	200(300)	300
Depot charging (kW)	22	22/44	44	2 x 43	44	44	44
Opportunity charging (kW)						150	2 x 150
Charge time (hours) to 80 %	8	2-8	3.5	5	8	4.5 (to full charge)	4-6/0.3 for slow charging/fast charging

3.3.2. Manufacturers and market outlook

Specifications of some electric trucks currently in use and their corresponding battery capacities are presented in Table 15.

Table 15: Specifications of some selected electric trucks [120].

Manufacturer	Commercial name	Type	Maximum weight	Battery capacity (kW h)	Range (km)	Energy consumption (kW h/ km)	Charging power (AC/DC kW)
Mitsubishi	eCanter	medium duty	7.5t	82.8	120	0.69	
BYD	T7	medium duty	11t	175	200	0.88	100/150
Freightliner	eM2 106	medium duty	12t	325	370	0.88	260
Volvo	FL Electric	rigid	16t	100–300	100–300	1.00	22/150
Renault	D Z.E.	rigid	16t	200–300	300	1.00	22/150
eMoss	EMS18	rigid	18t	120–240	100–250	1.00	22/44
Mercedes-Benz		rigid	26t	212	200	1.06	
Renault	D WIDE Z.E.	rigid	26t	200	200	1.00	22/150
Tesla	Semi	semitrailer	36t		480–800	< 1.25	
BYD	T9	semitrailer	36t	350	200	1.75	100/150
Freightliner	eCascadia	semitrailer	40t	550	400	1.38	260

Currently, Akasol is the leading manufacturer of commercial vehicle battery systems in Europe. They estimate an annual production capacity of 800 MWh at Langen site in 2020 (currently 300 MWh), additional 2 GWh in Darmstadt end 2021, combined with a planned US production line, Akasol expect to have a total production capacity of up to 5 GWh per year as of 2022 [121]. Akasol uses mostly NMC-type batteries, no further specifications are given.

3.3.3. Materials needs and compositions

Batteries used in heavy (e.g. trucks) and light (e.g. vans) commercial vehicles have similar chemistries as those used in personal vehicles and public transport vehicles. However, both size and shape of the cells and packs vary depending on the type of application [4].

In terms of battery composition, LFP batteries are expected to dominate the market for the next couple of years. However, like PVs and buses, the fastest growing market is expected from NMC batteries with 20.4% CAGR in terms of sales volume. LTO-based batteries are also forecasted to grow significantly [122] [123].

Some examples: BYD indicates that they use NMC batteries for their smaller trucks (T3: 2.6 tons, T6: 7.5 tons) and LFP batteries in their heavier trucks (i.e. T8: 18 tons, 217 kWh battery; T10: 31 tons, 435 kWh) [123]. The VW-owned company MAN reports to use NMC-type batteries (e.g. 36 kWh in the e-TGE), similar to Mack (LR BEV). The Dutch manufacturer EMOSS uses LFP batteries with capacities ranging from 60 – 320 kWh offering a range of up to 250 km.

3.4. Shipping and ferries

3.4.1. Status today

The world's first all-electric ferry (MF Ampere) started operations on the Lavik-Oppedal crossing back in 2015. The MF Ampere runs on 10 tons of LIBs and carries up to 350 passengers and 12 cars (20 min journeys with 10 min recharge). As of end 2019, 185 battery-powered marine vessels are in operation around the world (192 to be deployed until 2026), the largest part of which is located in Norway (followed by France), see Figure 54. The number of ships with batteries by ship type is depicted in Figure 55. It is planned that by 2022, over 70 battery-powered ferries will be in operation in Norway and as of 2030, Norway plans to have 2/3 of all the boats carrying passengers and cars around its coast to be electric [124].

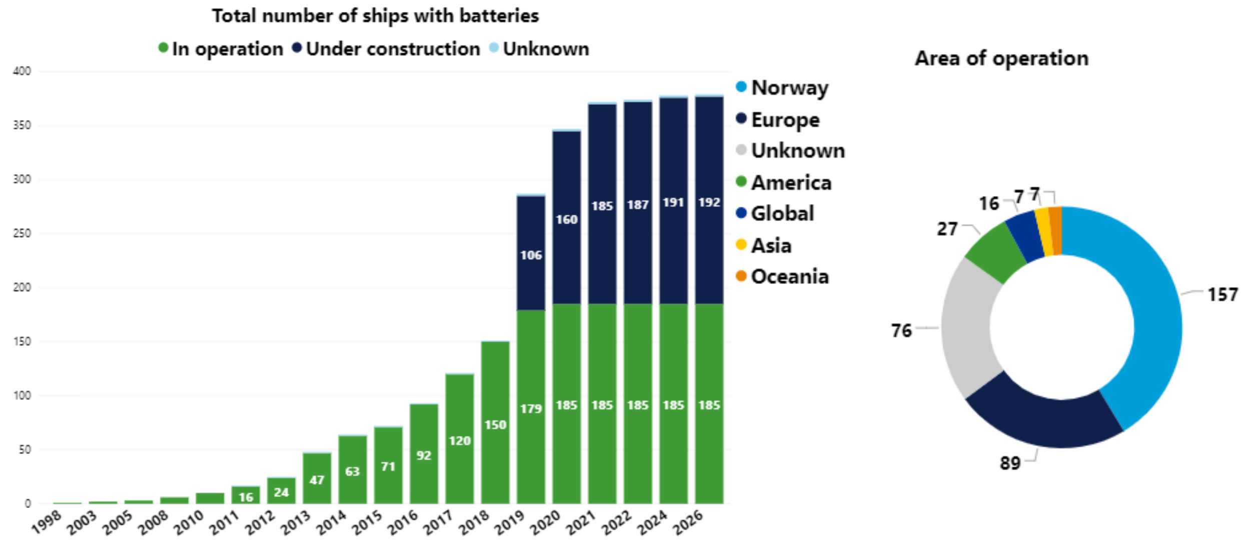


Figure 54: Development of the total number of ships with batteries worldwide (left) and area of ship-operation (right). Source: Maritime Battery Forum [125].

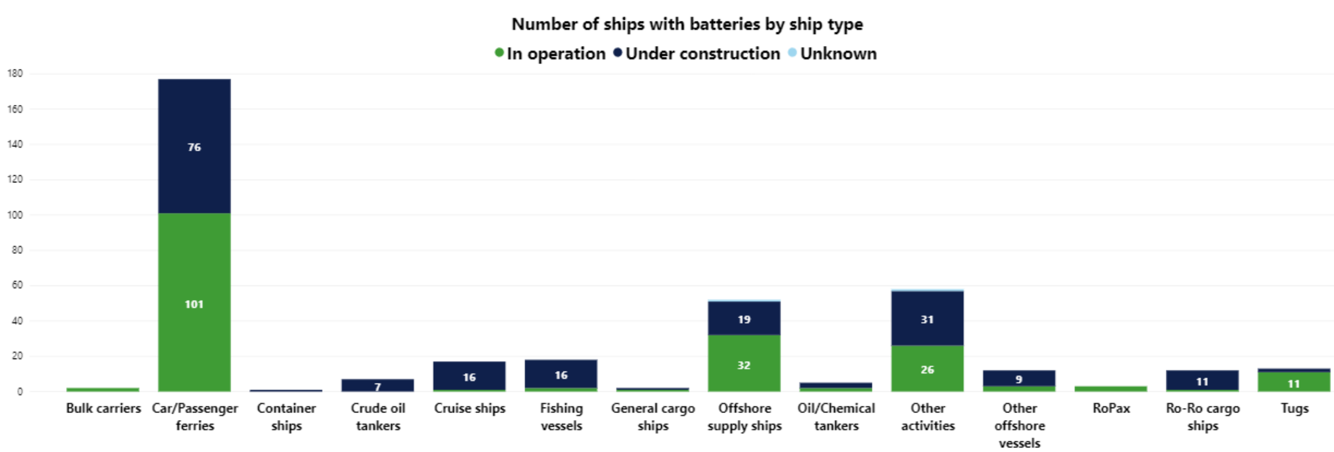


Figure 55: Number of ships with batteries by ship type. Source: Maritime battery forum [125].

3.4.2. Manufacturers and market outlook

As a result of the planned large investments in battery-powered ferries, Norway has a large part of worldwide output of maritime batteries. The market shares of the main suppliers of maritime battery systems are summarized in Figure 56.

Corvus Energy is currently the leading supplier of energy storage systems for maritime, offshore, subsea and port applications, totaling projects over 200 MWh. In September 2019, Corvus Energy opened a new battery factory with a capacity of up to 400 MWh per year in Bergen to meet the raising demand in the European market [126]. Their preferred cathode chemistry is NMC and they claim that their batteries are 99% recyclable [127].

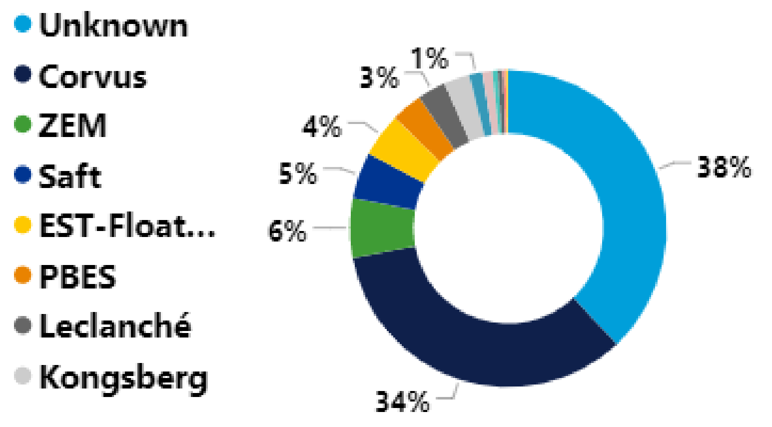


Figure 56: Battery supplier market share. Source: Maritime Battery Forum [125].

Early 2019, Siemens opened a battery factory in Trondheim (investment of around 100 mill NOK) with a yearly capacity of around 300-400 MWh, corresponding to batteries for 150-200 ferries per year [128]. Siemens is convinced that the maritime battery marked has a lot of potential for the future both, in Norway and worldwide: e.g. there are 5,100 fishing boats operating in Norway, 3,000 of which can be electrified.

Other maritime battery companies established in Norway are Elpro Solutions[1] (previously PBES, offering High Power NMC, Energy NMC and LTO configurations), Grenland Energy and ZEM. Despite the fact that about 90% of the battery modules are from Norwegian suppliers, most of the battery cells are still produced in Asia, mostly China [111][128].

3.4.3. Materials needs and compositions

Based on knowledge in projects related to the maritime sector in Norway, we know that the electric ferries deployed nationally are based on similar chemistries as PVs, with the most common cathode material being NMC [125]. A distribution of cell chemistries by the number of ships is shown in Figure 57. No detailed information on the type of NMC chemistry could be obtained.

[1] PBES used to be amongst the world's largest maritime battery producers but went bankrupt in 2018 and was taken over by Elpro Solutions. The production is still running in Trøndelag: https://www.tu.no/artikler/batterifabrikk-gikk-trondheim-konkurs-na-overtar-en-av-de-storste-kreditorene-produksjonen/434606

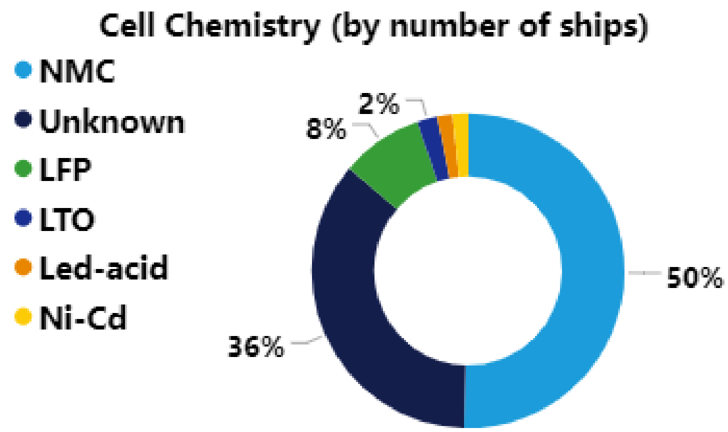


Figure 57: Battery cell chemistry by number of ships. Source: Maritime battery forum [125].

3.5. Stationary storage units

An overview over the technology mix in energy storage systems between 2011-1016 is given in Figure 58. According to IEA, this mix remains largely unchanged after 2016, with LIBs making up almost 85% of all new capacity installed [129].

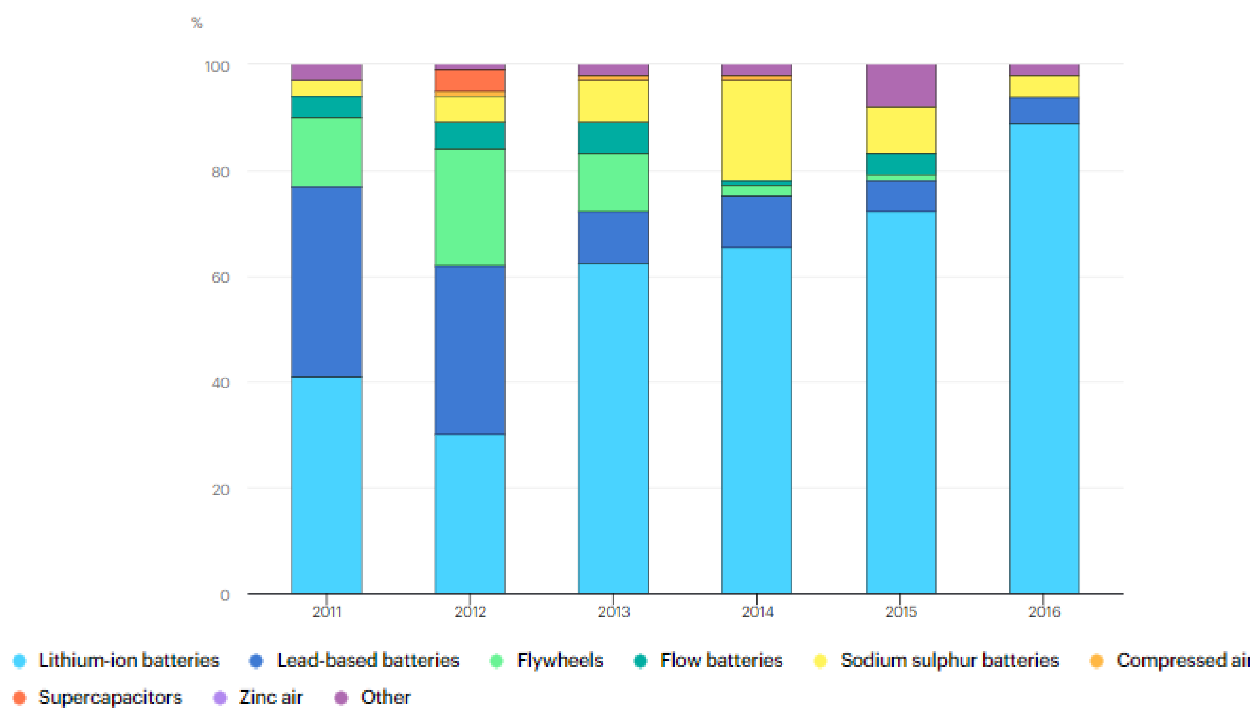


Figure 58: Technology mix in storage installations excluding pumped hydro, 2011-2016. IEA 2019 [129].

According to BloombergNEF, the number of energy storage installations (including 8 different battery types, no further details given; excl. hydro) will increase exponentially from 9 GW/17 GWh deployed as of 2018 to 1,095 GW/2,850 GWh by 2040 (cf. Figure 59). This growth will be facilitated by the increase in manufacturing capacity of LIBs driven by the booming EV market and the connected cost reduction (expected halving of the cost per kWh by 2030), as well as availability of 2nd life batteries (see Section 4.1). Bloomberg predict the total demand for batteries in the energy storage and electric transport sectors to be 4,584 GWh by 2040 [130].

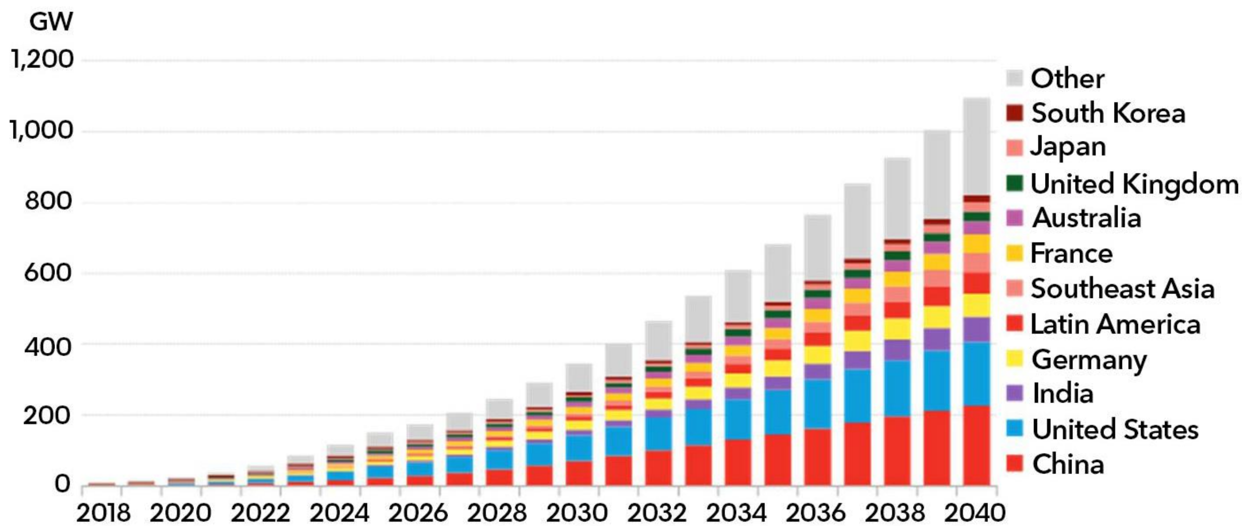


Figure 59: Global cumulative energy storage installations (excl. hydro). BloombergNEF [130].

In principal, there are five main energy storage applications: (i) Load Shifting, (ii) Peak Shifting, (iii) Grid Management, (iv) Ancillary Services and (v) Reserve Power. These all have different requirements on capacity, depth of discharge, durability, safety, cycle times, grid/utility requirements, space limitations, ambient environment and obviously cost (see Figure 60) [11]. The demand for energy storage installations by the type of storage application is shown in Figure 61.

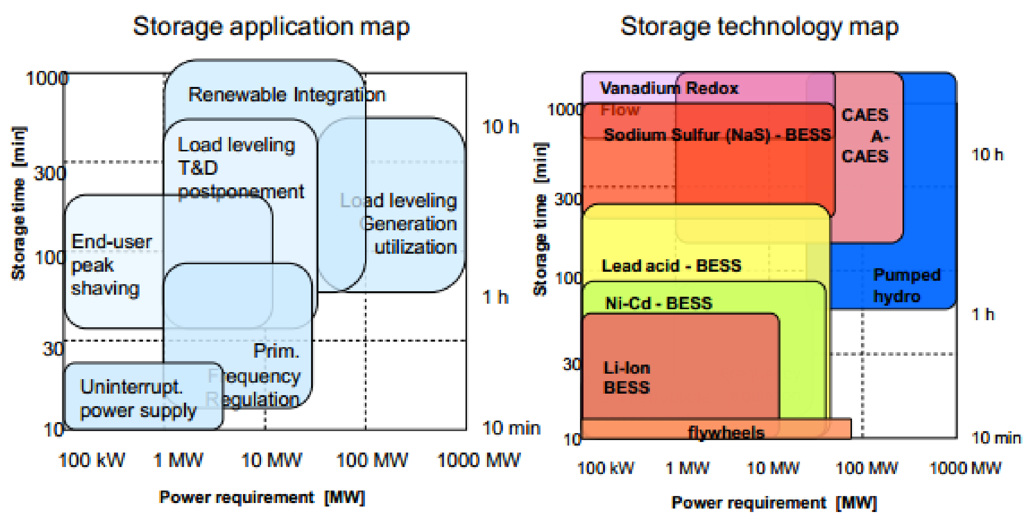


Figure 60: Storage application and storage technology maps. Source: ABB Group.

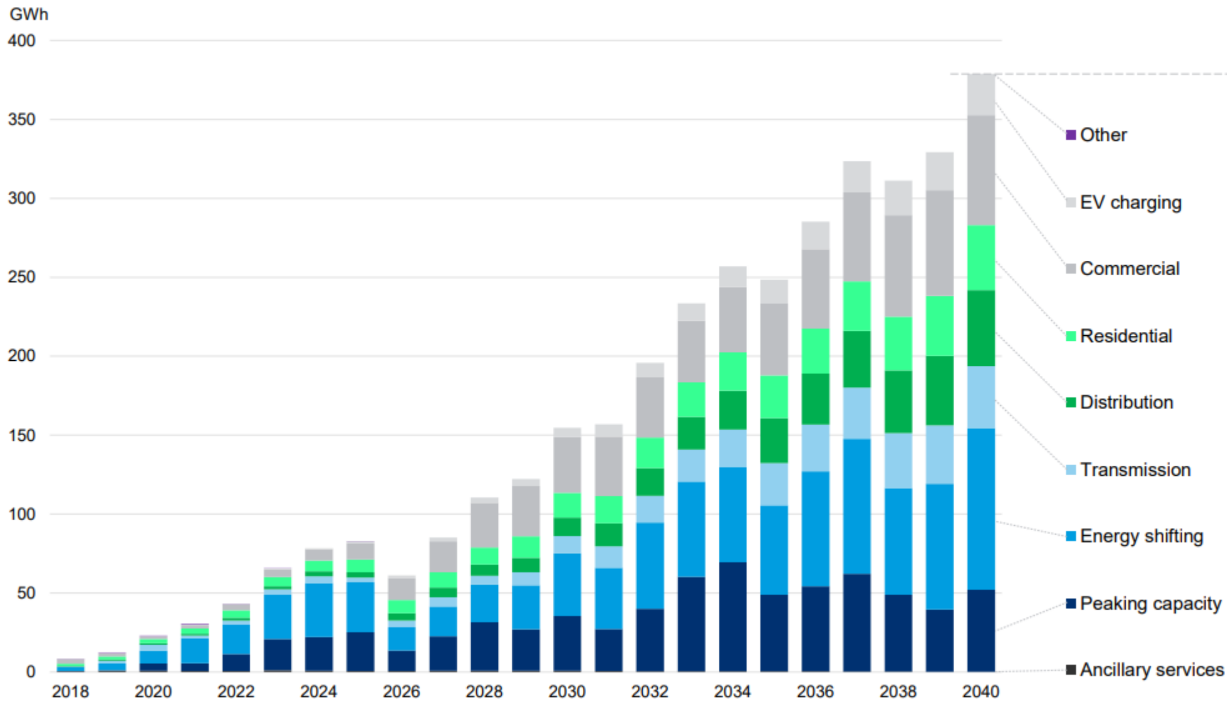


Figure 61: Global energy storage demand by type of storage application. Source: BloombergNEF via Freyr [131].

3.6. E-bikes and other niche markets

Previously e-bikes used lead-acid batteries, but they have also seen a shift recently to similar chemistries as personal EVs, but with a wide range depending on the manufacturer. E.g. LMO, LFP, LCO and NMC were all found in e-bikes in Denmark.

4. Recycling and reuse

Batteries are susceptible to degradation with time and age, with their lifespan depending on chemistry and use. In an EV, the End-of-Life (EoL) is normally defined when the battery reaches 80 % of its initial capacity [42]. At this time, the batteries are normally being replaced in the car, and their lifetime can either be extended through a second life (reuse), or they can be directly recycled, as seen in Figure 62. Even though the driving range is significantly reduced at the EoL criterion, the battery may still have enough capacity for less demanding applications, where the capacity-to-weight ratio is less important, e.g. for stationary energy storage.

Figure 62: The role of battery electric cars in the EU power system and beyond [132].

For both reuse and recycling, the batteries must be removed from the automotive application, and disassembled. Disassembly of battery packs from EVs is demanding, labor intensive and associated with numerous of hazards. Only manual disassembly exists on an industrial level today, but state-of-art robotics, computer vision and artificial intelligence (AI) for handling diverse waste materials exist and are now being adapted towards automatic disassembly of battery packs from automotive applications as well [133]. Apple for instance, has implemented an automated disassembly line for iPhone 6, that can disassemble one device in 11 seconds [134]. A challenge for the car industry is the variety of existing cells, modules and batteries packs as shown in Figure 63 for Tesla model S, BMW i3 and Nissan Leaf.

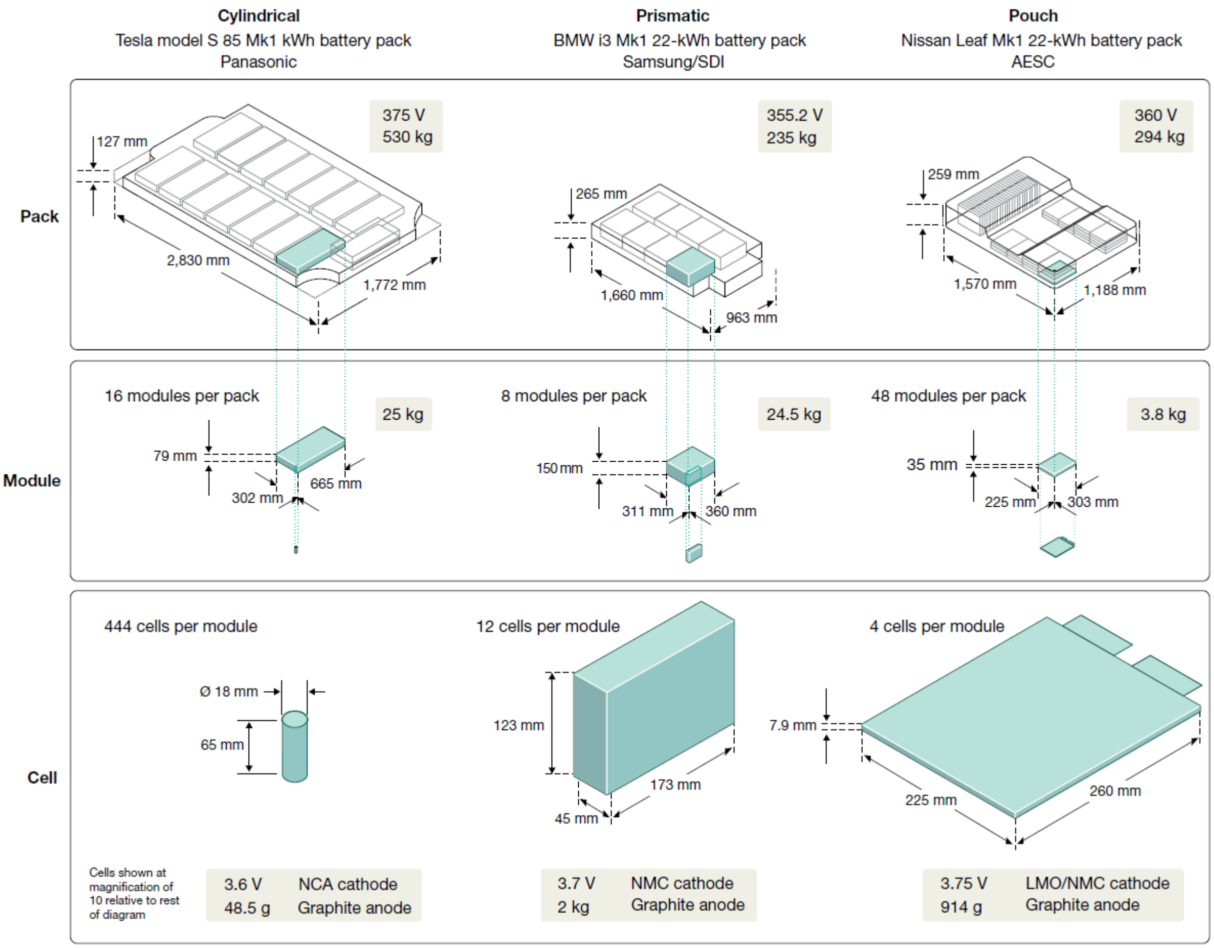


Figure 63: Illustration of the variety of battery cells, modules, and packs for used in Tesla model S, BMW i3 and Nissan Leaf electric vehicles. Figure adopted from [133].

4.1. Reuse (Second life)

Before being used for second life purposes, the EV batteries need to be tested in order to check their State-of-Health (SoH) and remaining capacity, to identify if reuse is a viable option, and if so, the best possible second use applications. The optimal tests must be non-destructive in-situ techniques for monitoring cells in service, to enable warning of possible cell replacement. Electrochemical impedance spectroscopy (EIS) can give information on SoH of cells, modules and potentially full packs, and are also an indication of ageing mechanisms, as lithium plating [135]. The preferable option from an economic point of view is to directly reuse the whole battery without dismantling it, since disassembly of battery packs, as mentioned, are highly labor intensive and thereby costly [136]. However, for most repurposing processes the battery packs must be disassembled to module level at least, and the process normally consists of several steps, including dismantling, potential separation and/or replacement of module, and reassembly into new packs before they can be reused in a new application [133]. Figure 64 shows an ideal life cycle of a battery with primary application in an EV, a second life in a stationary application, before being recycled and used for new EV batteries again.

Figure 64: Ideal life cycle for a battery with primary application in EV, second life application as stationary storage, before being recycled [137].

Due to the high market share of EVs in Norway (the new car sale of EVs reached a share of 50 % in 2019[1]) and the predicted future demand mentioned in Section 3.1 (see Figure 37), battery cells that are reaching EoL are increasing, and recycling and possible reuse of batteries are becoming more relevant. Bloomberg New Energy Finance (BNEF) estimates that there will be 95 GWh EoL EV battery capacity available globally by 2025, and that 26 GWh can be used in second life applications [138].

As second life use of batteries is becoming more widespread, there are several pilot projects set up in Norway already, e.g. Energipakke Borg Havn (E-land), Coop Klepp Jærhagen (Smartly), Bislett stadium (Eaton/Nissan), xStorage HOME (Eaton/Lyse/Nissan) and Power Bank for e-car (Volkswagen). In all these projects, second life batteries are used for stationary energy storage combined with solar photovoltaic (PV) panels.

4.2. Recycling

The batteries that comes into recycling differ in size, shape and chemistries as mentioned. In addition to handle the diversity of batteries and battery packs, the recyclers must ensure safe and proper management of any dangerous components. Today, there is a large deviance between production rate and recycling rate for LIBs. At EoL, most of the Li-ion batteries are being hoarded in households (estimated to be as high as 95 % of produced LIBs globally) or goes to landfill, while only a limited number are being recycled [139]. In addition, there are further losses of battery components due to current recycling processes being limited to components with high economic value as Co, Cu, Fe and Al [140]. The low recycling rate may be attributed to several

[1]OFV – registered 48,4 % of new car sales as zero-emission cars from January-June 2019

factors as inefficient collection systems, deficient legislation, and lack of feasible recycling technologies. Several of the common battery components (Co, Ni, Cu) are initially produced from sulfide ores with low metal concentration. Their primary production is therefore energy-intensive with significant sulfur oxide emissions. All the considered recycling processes recover these materials with reduced emissions. However, the processes are highly resource intensive, and thus strongly influenced by economic regulations. The methods used, and their efficiencies vary, with the main recycling processes described below [141].

Pyrometallurgical recycling involves use of high temperature furnaces to recover some of the metallic battery components. Copper, cobalt, nickel and iron are reduced to a molten alloy which is normally separated and sent to refineries for further processing. A furnace slag, mainly containing ashes of burnt lithium, aluminum, silicon and calcium may also be recovered, but it is still uneconomical. An advantage of this technology is that all battery chemistries can be recycled simultaneously, but the process is energy intensive and results in large CO_2 emissions.

Hydrometallurgical recycling involves the use of acids to dissolve metal components of batteries. The recovery rate is high (may reach > 99% for Al, Co and Li [142]), and any metal can be recycled, but the process is cathode specific. Disadvantages include release of toxic gases, large amounts of chemical reagents and high costs.

Mechanical or physical recycling consists of dismantling of the battery pack and mechanical and/or physical separation of battery components (e.g. electrodes, wiring and casing), with the goal to recover components in original state. This is an immature technology which is still under development. It can be combined with pyro- or hydrometallurgical methods to recycle components that are not reusable or recovered in the original process.

Recycling and recovering of the graphite anode have not been extensively researched. But, as mentioned in Section 1.2, natural graphite is on the list of critical raw materials. Due to the rapidly increased demand for lithium ion batteries, and the number of spent batteries, reusing recycled graphite in LIBs to form a fully closed-loop is important and necessary. In 2019 Ma et al. reported a scalable high-quality recycling process to recover graphite, based on a hydrometallurgical process [143].

Large scale recycling of LIBs is mainly performed in China (seen in Figure 65), but there are also recyclers in several European countries, in the US, South Korea, Canada, Japan and a few other countries. The reason for the relatively low recycling rate in Europe is that most of the recyclers outside China and South Korea lack a direct connection to the battery material market. The batteries are therefore exported to or sold for reuse in Asia [144].

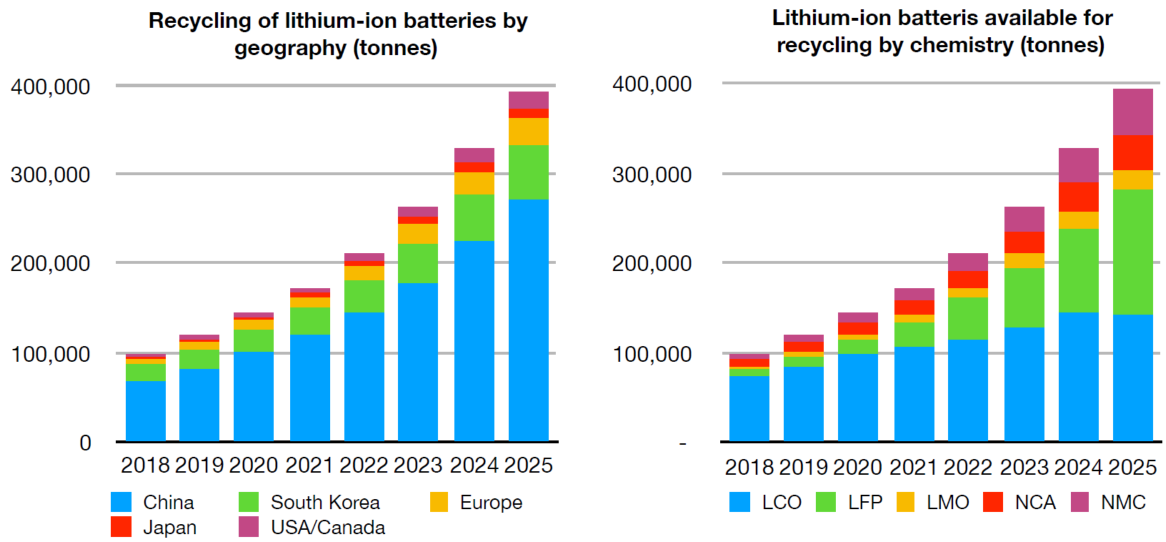


Figure 65: Recycling of LIBS by geography (left) and chemistry (right) [144].

Most of the batteries that reach EoL today have mainly been used in portable electronics, where a large proportion has an LCO-cathode with a high Co-content as seen to the right in Figure 65. With high cobalt prices, these are attractive and highly profitable to recycle. This will probably change in the future due to the trends and extensive research towards Co-reduction and Co-free cathodes as mentioned in Sections 1.3 and 2.2.

5. Summary

The major trends for future chemistries and new technologies can be summarized as seen in Figure 66. At the moment we have a variety of different cathodes in use for the different segments; LCO for portable electronics, NMC and NMC/LMO for electrical personal vehicles, and LFP for public transport vehicles. As the battery demand will increase with the projected increase of EV production, the trend goes towards more use of NMC cathodes with introduction of an anode with higher capacity. The personal vehicle segment will be the main driver of the future chemistries needed, thus the NMC cathode will be the most prominent one, although smaller EV segments might still prefer cathodes such as LFP. The more disruptive technologies such as solid state (which in turn might enable Li-air, Li-S) are not expected to have a large share of the marked until after 2025.

The earlier sections describe in more detail the expected evolutions within each segment and for the anodes and cathodes in general.

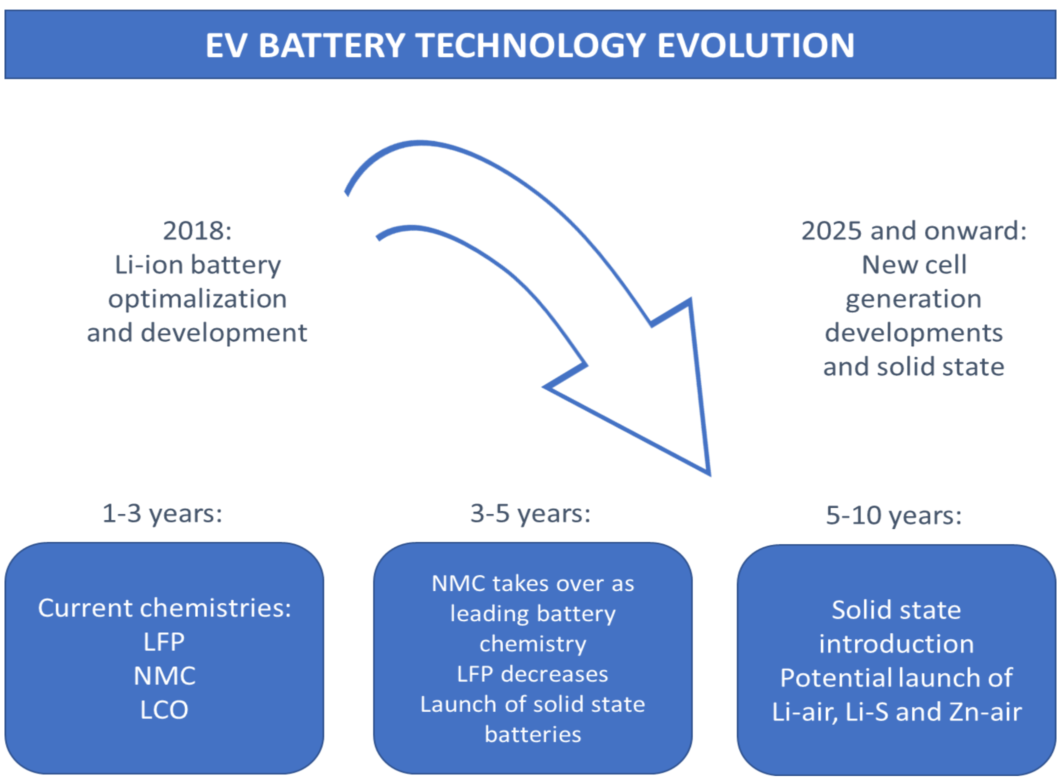


Figure 66: The EV battery technology trend in the next future (<10 years). Adapted from Djukanovic [4].

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Appendix A1. Recommended literature

A1.1. Raw materials

Name of report	Publication year	Author	Reference
Report on Raw Materials for Battery Applications	2018	EU Commission Staff Working Document	[3]
A Vision for a Sustainable Battery Value Chain in 2030	2019	World Economic Forum/Global Battery Alliance	[17]
From mine to car: Fully integrating Europe's supply lines	2019	McKinsey (Battery Materials Europe presentation)	[75]
Li-ion battery materials: present and future	2015	Nitta et al.	[1]
Lithium and cobalt – a tale of two commodities	2018	McKinsey	[50]
The EV revolution: impacts of critical material supply chains	2019	Roskill	[7]

A1.2. Battery reports

Name of report	Publication year	Author	Reference
Norway – unique location for battery development and production		Innovation Norway	[111]
Li-ion battery value chain and related opportunities for Europe	2017	European Commission: JRC Science for Policy Report	[35]
ORAMA – Technical guideline tools for harmonizing of data collection on batteries	2019	ORAMA	[93]
Mapping of lithium-ion batteries for vehicles – a study of their fate in the Nordic countries	2019	Nordic council of ministers	[52]
A vision for a sustainable battery value chain in 2030	2019	World Economic Forum/Global battery alliance	[17]
Future brief: Towards the Battery of the Future	2018	European Commission: Science for Environment Policy	[40]
Global EV Outlook 2019	2019	International Energy Agency	[95]
The Lithium Ion Battery and the EV Market	2018	BMO Capital Markets	[145]

Appendix A2. Market forecasts

Table 16: Summary of different reports for market shares of cathode chemistries (see Figure 20) [7], [24], [50], [16].

	2018		2020					2025					2030		
	Av	Roskill	Av	McK	Roskill	BNEF	BMO	Av	McK	Roskill	BNEF	BMO	Av	McK	BNEF
LCO	11	16	8		9			4		3			2		
LMO	5	7	3	2	4		3	1	1	2		1		1	
NCA	9	12	7	26	12	41	10	6	24	9	36	10	6	14	34
NMC-9.5.5		2			2				2					37	
NMC-811			2	32	2	8			35	28	46	2	15	25	58
NMC-622		1	11	40	4	13	25		38	12	14	60	31	23	8
NMC-532		30	20		35	33				7	4		32		
NMC-111		7	24		6	5	40			1		7	9		
NMC	41							75							
LFP	34	25	26		27		22	13		37		20	5		

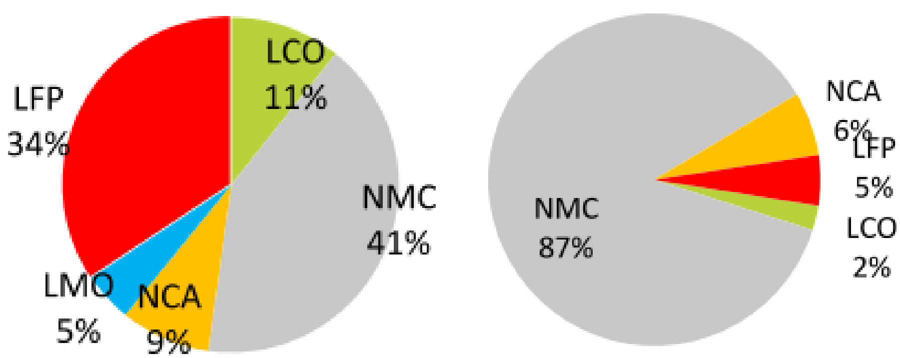

Figure 67: Market shares between cathode chemistries in 2018 (left) and 2030 (right). (2018: total cathode market 345 000 tons; 2030: total cathode market 1 670 000 tons) [24]

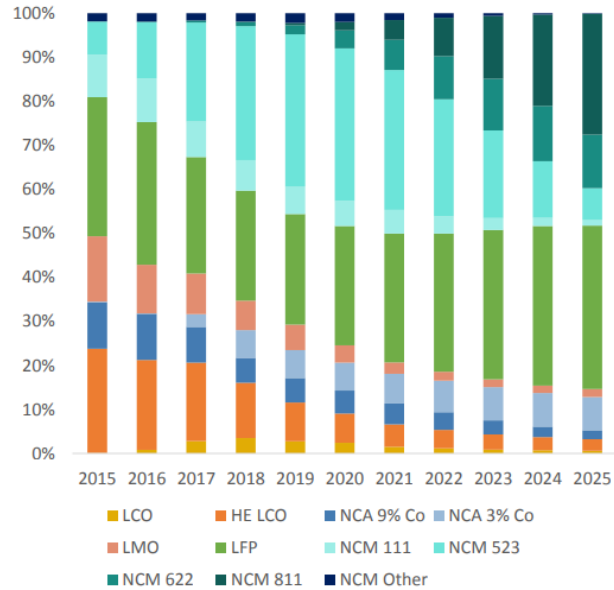

Figure 68: Cathode usage by type presented by Roskill in 2019 [7]

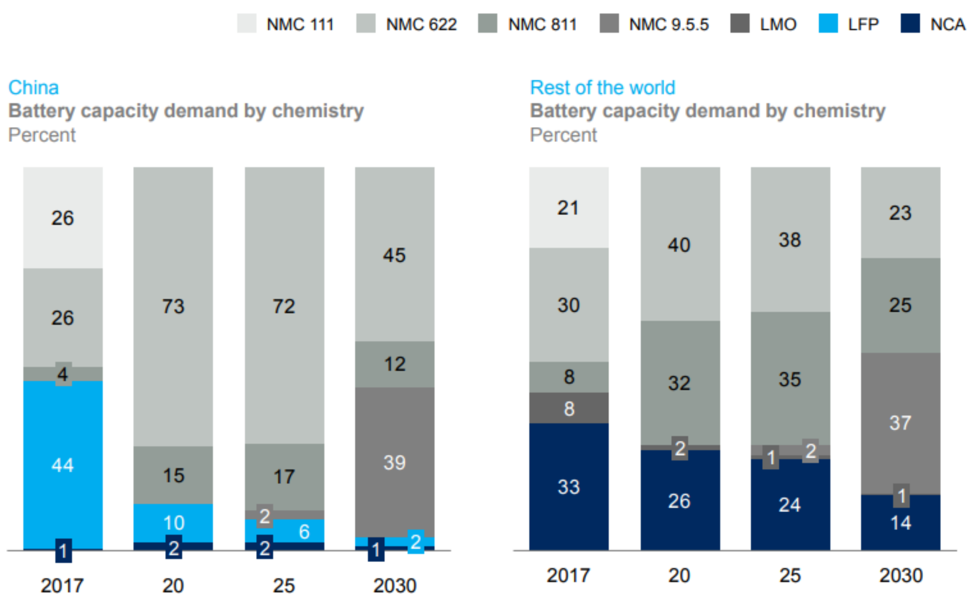

Figure 69: EV demand by chemistry in China and the rest of the world. Reported numbers from McKinsey in 2018 [50].

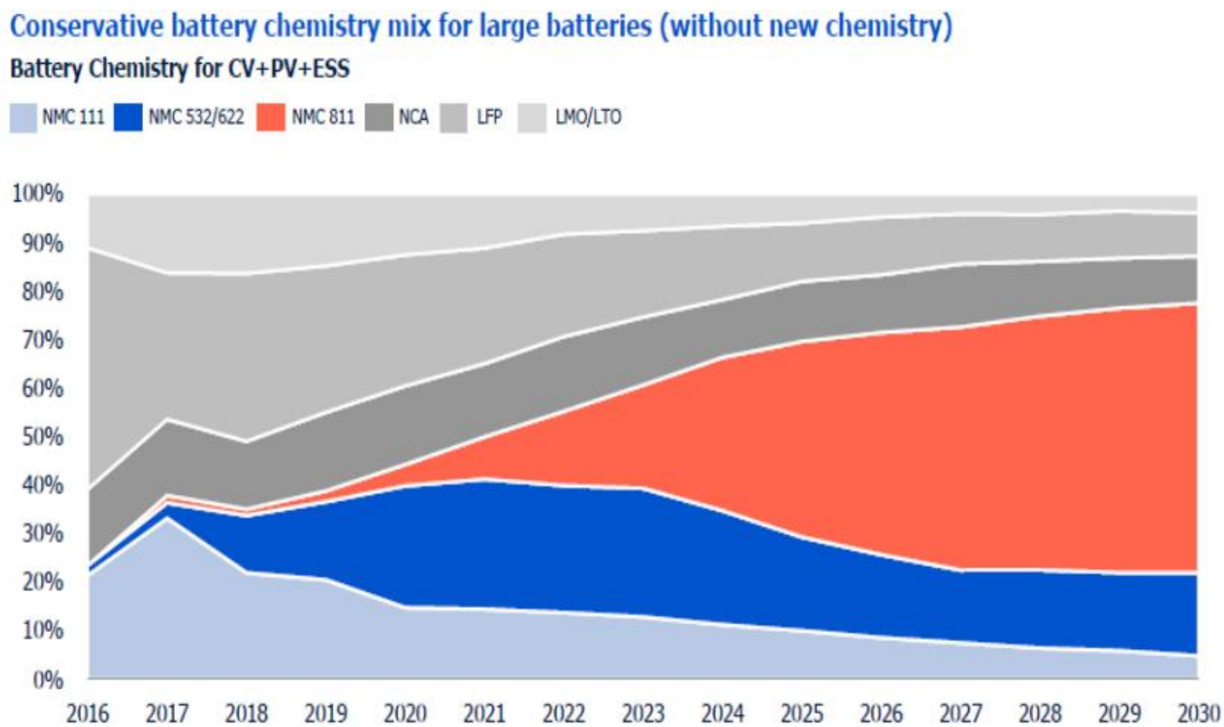

Figure 70: Li-ion battery chemistry mix for large batteries forecasted into 2030 [4].

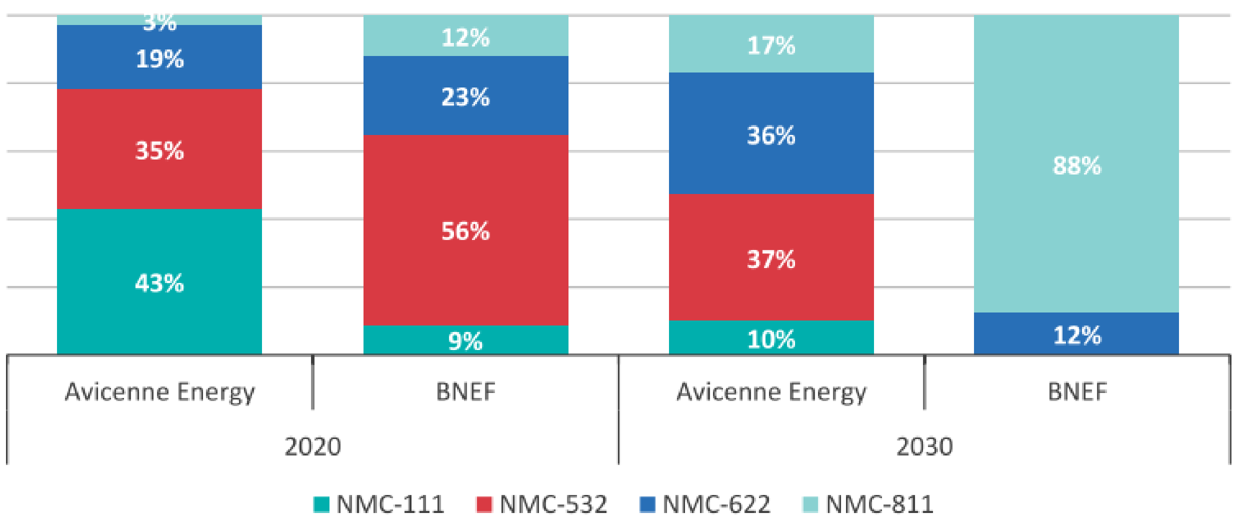

Figure 71: Future NMC chemistry mix in cathodes based on reports by Avicenne Energy and BNEF [34].

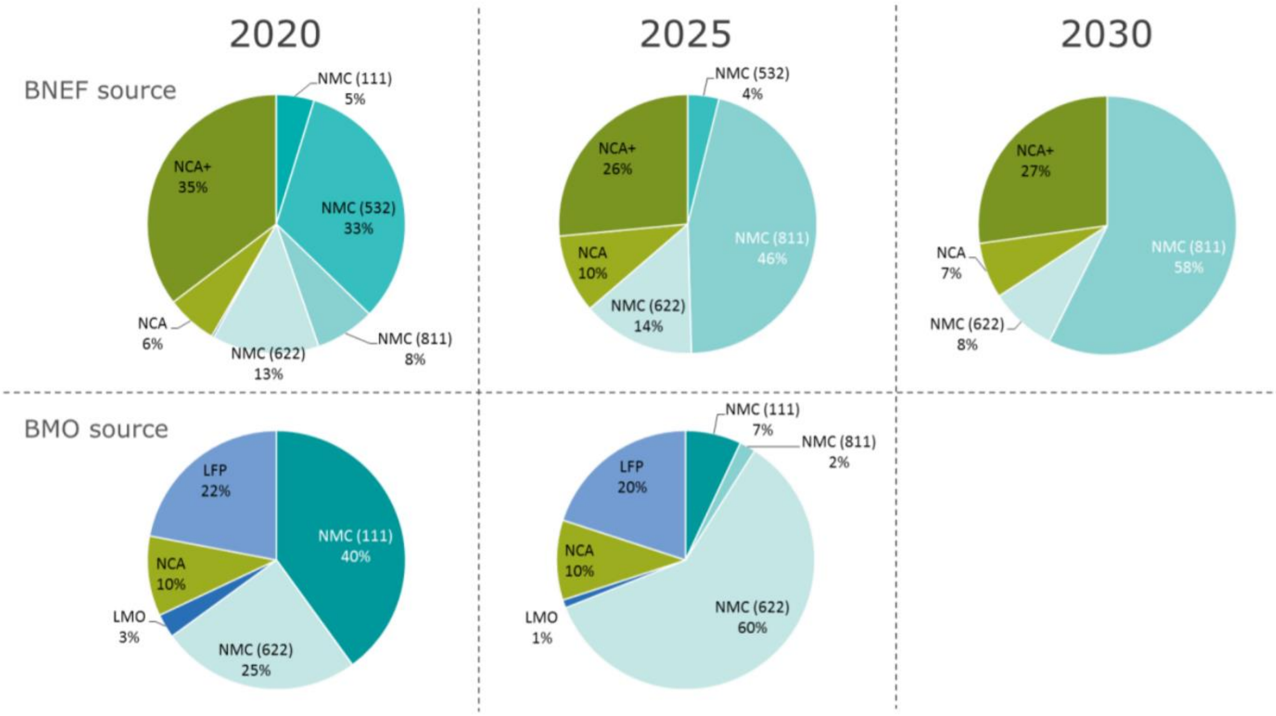

Figure 72: Expected development of cathode materials by BMO and BNEF [16].

Copper Content by Electric Vehicle Type

The total copper content among the spectrum of electric vehicles includes the following:

- Electric bus – 224-369 kg of copper per vehicle.
- Electric vehicle – 83 kg of copper per vehicle.
- Plug-in hybrid electric vehicle – 60 kg of copper per vehicle.
- Hybrid electric vehicle – 39 kg of copper per vehicle.

Figure 73: Copper content by segments [146]