LIB TECHNOLOGY MAPPING REPORT

UPDATE 2021

Update to the 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 the second deliverable in work package 1; Technology Mapping, led by Institute for Energy Technology (IFE). The first deliverable (2019) was a report describing the technology status of current and future lithium-ion battery (LIB) chemistries. The report was used as an input to the material flow analysis to strengthen the forecasts, and this update should be read together with the first report.

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 the previous report is already in need of an update. This updated report, the second deliverable of WP 1, will have a closer look at what has changed since our outlook in 2019, update numbers and fact and establish the major trends in the battery technology development.

Kjeller, May 2021

Authors:
Julia Wind
Carl Erik Lie Foss
Hanne Flåten Andersen

Introduction and overview of major developments in 2020

Alongside continuously decreasing LIB prices across all sectors (from around 1000 $/kWh in 2011 down to just over 100 /kWh in 2020), battery demands are continuing to increase. There is general agreement that the main contributor to the increasing LIB demand is the electric vehicle (EV) market. The stationary energy storage sector (ESS), currently amounting to around 5 % of the LIB market, is also expected to grow significantly over the next decades, with storage related to PV expected to amount for over half the installed capacity. Predictions on the actual demand growth vary significantly (cf. Table 1): in a recent EU report*, the global demand was estimated to surpass 1000 GWh around 2025 and reach around 2600 GWh by 2030, with the EV battery demand in Europe amounting to around 400 GWh in 2030).

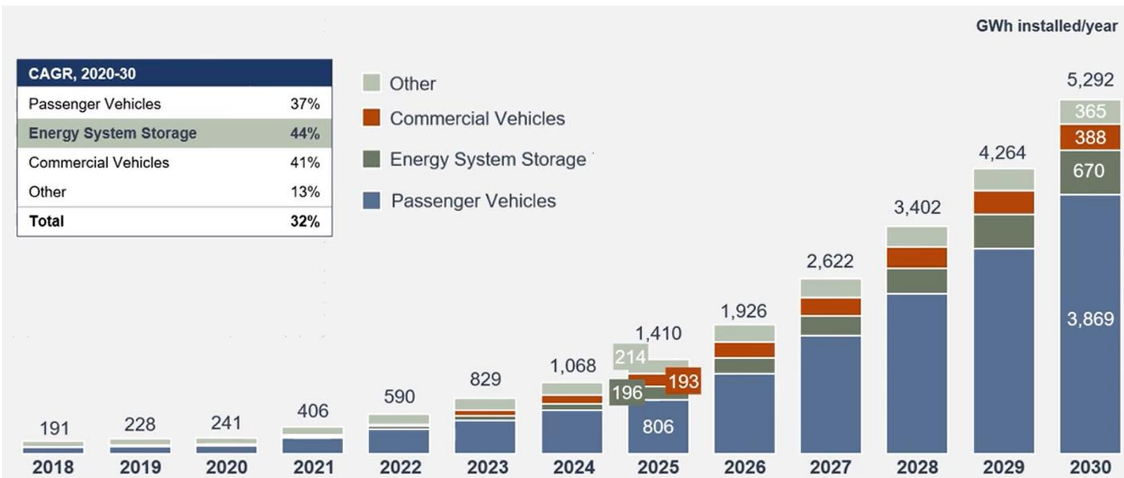

Figure 1: Global Battery demand by sector (Source: Freyr at WATTS Up 2021).

According to a study by Rystad Energy (presented by Freyr at WATTS Up 2021), the projected global battery demand by 2030 is almost double, reaching approximately 5300 GWh (cf. Figure 1). Simultaneously, only 1600 GWh production projects have been announced, amounting to a shortfall of 3700 GWh, corresponding to 115 Gigafactories (32 GWh per factory). Excluding China in this projection, the world is expected to run into a cell production shortage already by 2023/2024.

Table 1: Global battery demand predictions.

	2020		**2025**		**2030**	
	EU	Freyr	EU	Freyr	EU	Freyr
EV	229	-	808	999	2333	4257
ESS	10	-	105	196	221	670
European demand	32	-	170	-	443	-
Total	*282*	*241*	*971*	*1410*	*2623*	*5292*

Figure 2 summarizes expected trends in battery capacity demands within the EU, including minimum and maximum and average predictions for personal and commercial EVs as well as ESS applications until 2050.

* https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf

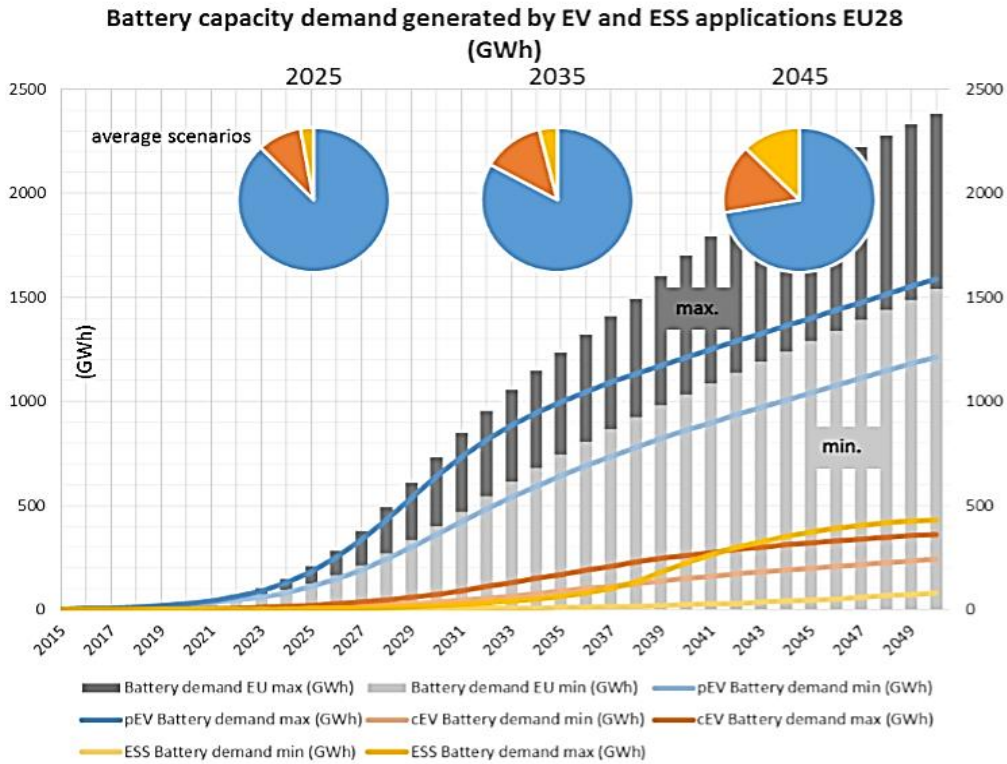

Figure 2: Battery capacity demand generated by EV and ESS applications within the EU28† (pEV: personal EV, cEV: commercial EV).

Unsurprisingly, many new developments have happened within the entire battery value chain since the last version of the BATMAN WP1 report was published late 2019. Figure 3 summarizes the popularity of research and innovation topics by battery component: Innovations on the materials level primarily take place within academia. Research interests are dominated by anode, electrolyte, and cathode, amounting to almost 90% of all battery related publications in 2020. The focus of industrial innovations, illustrated by the number of patents, is in the areas of battery management, battery packs and current collectors.

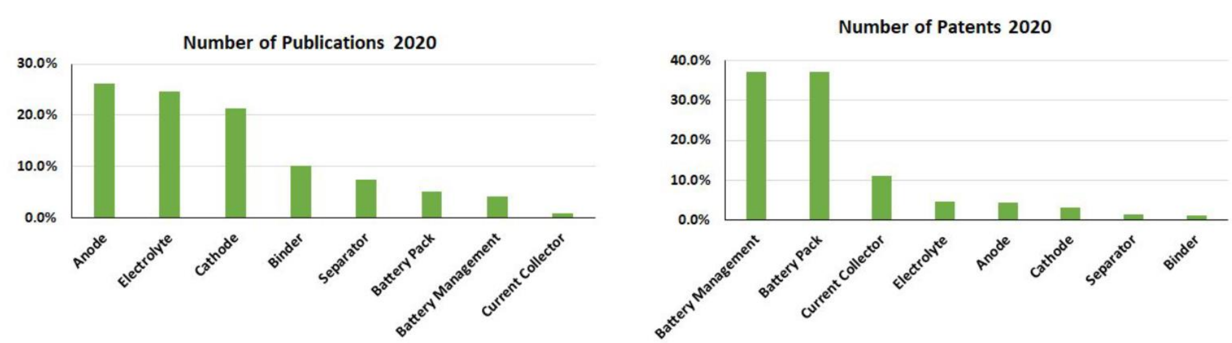

Figure 3: Ranked research and patent popularity by battery components (Battery bits report/google scholar).

In the following, we will update most relevant numbers and predictions from our 2019 report, as well as summarize and highlight selected developments within 2020, starting off with a brief summary on two

† Webinar: "One Hour with Europe: The New Batteries Directive and Its Impact on Future R&I Activities in the Sector"

recent events: Tesla Battery Day in September 2020, and, even more recent, Volkswagen Power Day in March 2021.

Tesla Battery Day 2020

Changes along all stages of the battery chain were presented, to improve range, production and costs for EVs. Tesla's largest announced improvements are to be expected within engineering and design, while being rather conservative on developments related to materials and next-generation battery technologies. Innovations on the **cell design** include their *4680 cells* (about double in diameter and slightly taller compared to the current 2170 cell) with *tabless electrodes*. Their patented tab-less design laser patterns the overhang current collectors into many small tabs, allowing for a more uniform current distribution along the approximately 5x longer electrodes. Additionally, Tesla announced the integration of the 4680 cells as structural elements in their cars, simplifying pack and module design while simultaneously compensating for the lower packing efficiency of cylindrical cells compared to similar pouch cells (leading to a 7 % cost reduction at pack level, and 14% range improvement). With respect to **electrode materials**, Tesla announced to use cheaper raw silicon, buffering the expansion with a conductive polymer electrolyte. However, the amount of Si to be included in the anodes remains unclear. No unexpected announcements were made on the cathode side, continuing efforts to reduce Co-contents following high-nickel, and LFP approaches. Regarding **production efficiency**, Tesla is looking into Maxwell's dry coating technology, so far looking promising on the lab-scale, but facing challenges when it comes to upscaling. The dry coating process (powder-to-film) would be a drastic innovation, leading to a significant reduction in production energy and thus cost, as well as it would replace the need for the use of toxic solvents.

Volkswagen Power Day 2021

Following Tesla's Battery Day, Volkswagen also revealed their EV plans up to 2030 during their Power Day in March 2021, addressing various aspects, such as cost, charging and sustainability[‡]. As opposed to Tesla's cylindrical cells, VW introduced a standardised hard-case **prismatic cell** format to be used in about 80% of their products. VW's **chemistry plans** on the other hand are more diverse: For their entry level cars, they plan to use LFP cathodes, high-Mn cells for most of their cars (for details see section on cathodes below), and NMC for selected applications. Anode chemistries are left more open, mentioning graphite, silicon and solid-state + Li-metal. VW's strong venture towards **solid-state** is their key differentiator from Tesla's roadmap. Owning about 20% of the start-up QuantumScape, VW plans to integrate the solid-state technology into their vehicles after 2025, promising a 30% increase in range with a 12-minute charge. VW also announced their plans on ramping up their contribution towards the European Green New Deal by opening 6 giga factories of 40 GWh capacity each in Europe, commencing in 2023, with their first two factories planned in Skellefteå (Northvolt) and Salzgitter. Salzgitter will also be the place for their recycling pilot line, aiming for a 95% cell recycling rate (although unclear whether this rate is a proven yield or a theoretical maximum).

Overall, Tesla announced total cost savings of 56% vs. VW 50%, splitting up into cell design: 14 vs 15%; manufacturing: 18 vs. 10%; electrodes 17 vs 20% and integration 7 vs 5%.

[‡] https://www.volkswagenag.com/presence/investorrelation/publications/presentations/2021/03/2021-03-15_PowerDayVWGroup.pdf

Raw Materials

Based on very recent predictions for material demands for EVs by Xu *et al.*[1], Co, Li and to a smaller extent Ni, are considered to be most critical with regards to upscaling of production capacities, reserves and supply risks. For all other materials used in LIBs, currently know reserves are expected to exceed future demands. This is also the case for graphite, due to the increasing use of synthetic over natural graphite, following synthetic graphite's superior performance and decreasing costs. Thus, in the following, we will focus on updates on cobalt, nickel and lithium, the bottleneck materials for the battery industry. While the Li demands are largely independent of the actual Li-ion technology development, especially the use of Co and Ni are strongly dependent on the Li-ion chemistry, more specifically, the cathode chemistry. Key numbers for these raw materials are summarized in Table 2 and described in more detail below.

Table 2: Summary of global demand /global supply in multiples between 2020 and 2030, and 2020 and 2050.

	2020 Mt for EV	2030 growth multiple demand/supply	2050 Mt / growth multiple for EV	2050 Recycling potential
Li	0.036	x5 / x3	0.62-0.77 / x17-21	- 20-23%
Co	0.035	x2 / x1.5	0.25-0.62 / x7-17	- 26-44%
Ni	0.13	x6 / x3	1.5-3.7 / x11-28	- 22-38%

Lithium. As LIBs are expected to continue to dominate the market in the foreseeable future, Li demands are naturally expected to increase. The highest demand for Li comes from the EV sector: Xu *et al.*[1] estimate a rise in Li demand for EV batteries by a factor of 17-21 from 2020 to 2050, i.e., from 0.036 Mt to 0.62-0.77 Mt. BNEF (cf. Figure 4) predict a Li demand of ~0.2 Mt for passenger EVs, and ~0.37 Mt total for 2030, with lithium supplies only being expected to grow up to ~0.28 Mt.

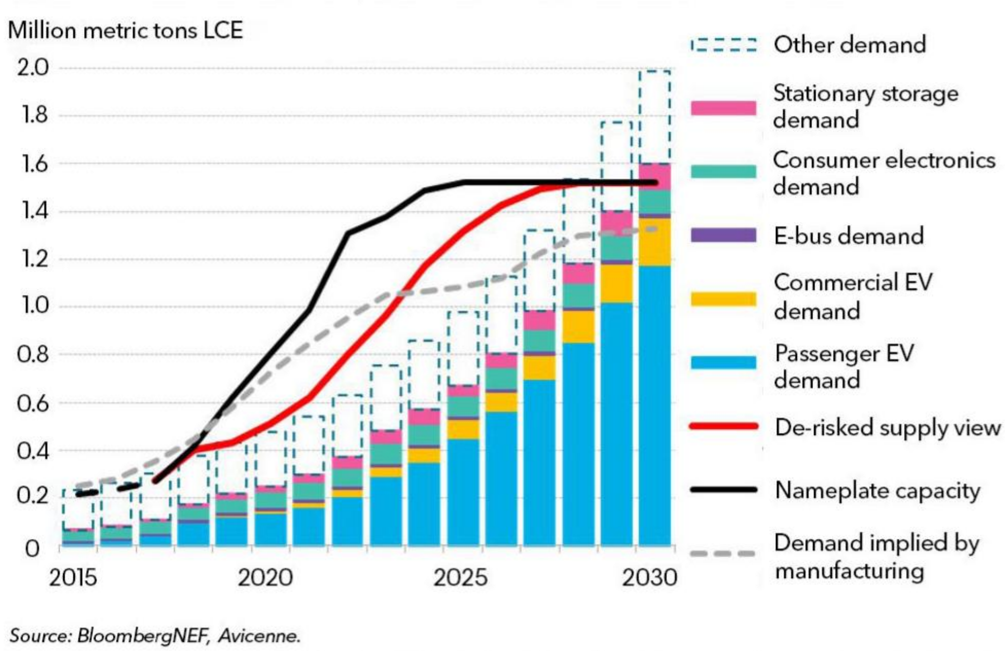

Figure 4: Global lithium supply and demand forecast. (Source:BNEF, Avicenne).

Compared to numbers in our previous report, the total lithium carbon equivalent (LCE) forecast has been adjusted and increased from around 0.7 Mt LCE to almost 1 Mt LCE for 2025, with the expected percentage taken up by Li for EV batteries increasing from 38% to almost 50%. In comparison with Avicenne's predictions from 2019, Li demands were adjusted up from 0.58 Mt to 1.6 Mt in 2030 for battery applications only. Major problems regarding the Li-supply are the highly concentrated geographic Li reserves, as well as the Li supply chain's large carbon footprint, imposing a large need on innovation, especially on producing battery-grade Li.

Cobalt. Despite the general trend towards low-or-no-cobalt cathode chemistries (e.g., high-Ni NMCs, see below), recent scenarios project a 1.5x increase in Co-demands between 2020 and 2030. This results in a potential Co deficit as early as 2022 or 2023, and a deficit of 149 kilotons only within the next 10 years (see Figure 5). Figure 6 shows the results from a more detailed study by Xu *et al.*[1], considering the influence of several different scenarios on the Co-demand development. Their results clearly indicate the opportunities in the development of new battery technology on the reduction of the dependency on Co. Due to the fast growth of the EV market, battery recycling offers the potential to reduce Co-demands by 26-44% only[1].

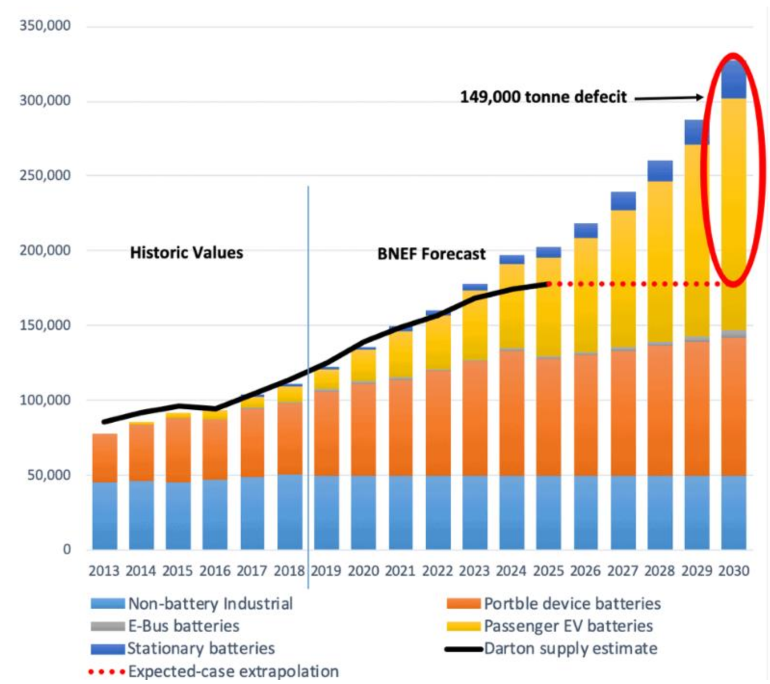

Figure 5: Cobalt supply and demand (Source: BNEF, Investor Intel§).

§ https://investorintel.com/markets/technology-metals/technology-metals-intel/cobalts-time-to-shine-will-come-again/

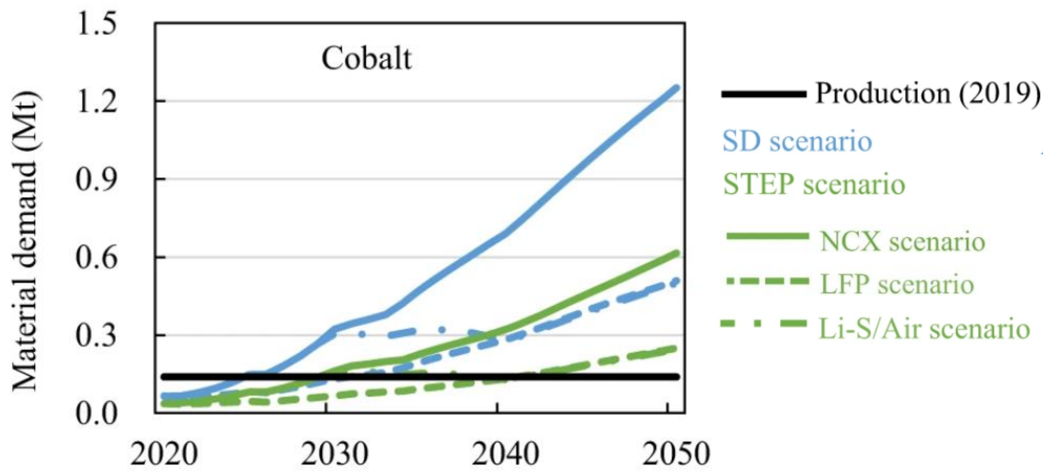

Figure 6: Global cobalt material demands for EV batteries for different scenarios from 2020 to 2050. STEP: Stated Policy scenario (incorporating existing government policies); SD: Sustainable Development scenario (including climate goals of Paris agreement). NCX scenario: continuing trend of NMC and NCA chemistries; LFP scenario: possible increased use of LFP in EVs. Li-S/Air scenario: possible break-throughs in Li-S/Air batteries. (Source: Xu et al.[1]).

Nickel. With the industry moving towards high-Ni cathode chemistries, Ni demands, especially class-1 Ni, are expected to substantially increase. Roskill expect that the battery sector will take up to 25% of the total Ni market by 2030[**], (with stainless steel continuing to dominate the Ni demand). Even though Ni resources are not as critical as Li and Co, already in 2040 EV batteries alone could use up as much as the global primary Ni production in 2019. Estimated Ni-demands for EV batteries in 2050 are expected to be around 1.5-7.6 Mt[1], strongly depending on trends in required future EV battery capacities. The recycling potential for Ni is estimated to be around 22-38% until 2050.

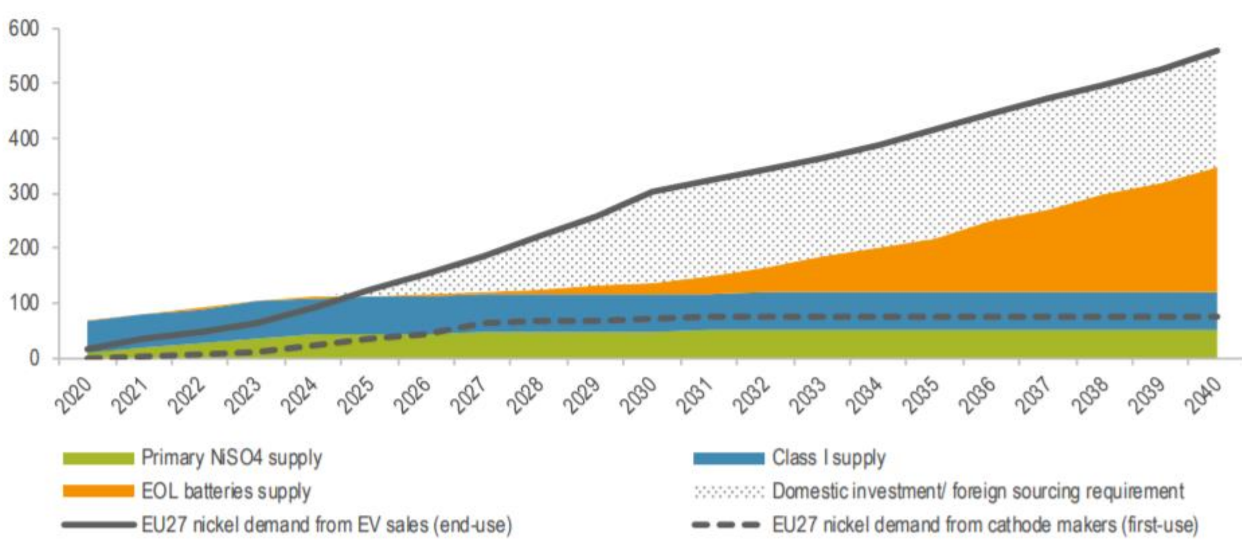

Figure 7: EU27 refined nickel supply and battery demand balances 2020-2040 (kt Ni). The volumes of Class I supply shown are not considered to be fully available for conversion to sulphate/directed toward the battery industry. Availability of such is dependent on EU 'critical demand' from other Class I consuming industries (Source: Roskill, 2020).

[**] https://nanthavictor.com/2020/07/22/nickel-demand-from-the-batteries-sector-to-account-for-over-25-percent-of-the-total-nickel-market-by-2030/

Although non-nickel battery chemistries are gaining increased attention, mainly due to their lower costs, nickel-containing LIBs will still be of high importance, especially for the transport sectors, due to their higher energy densities, implying longer driving ranges with smaller and lighter battery packs.

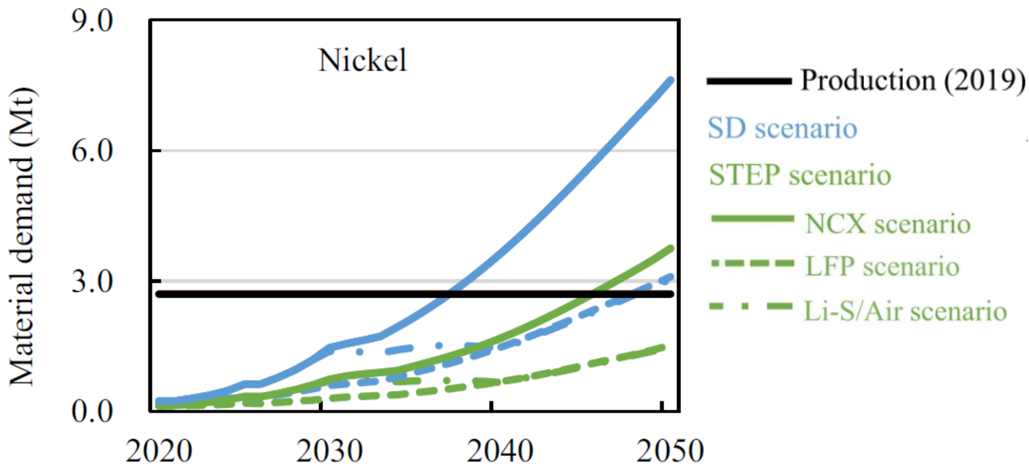

Figure 8: Global Ni material demands for EV batteries for different scenarios from 2020 to 2050 (Source: Xu et al.[1]).

Present and future battery technologies

The special issue of from Journal of Power sources*: Focus review - New and emerging battery technologies*[2], provides a good overview of the status of current and emerging technologies to reach the European Commission (EC) goal of carbon neutrality by 2050[3]. The following technologies are currently the most studied to reach this goal:

- Lithium ion[4]
- Lithium metal (including lithium-sulfur and lithium-air) batteries[4]
- Sodium ion and sodium metal batteries[5]
- Zn and Zn-Air batteries[6]
- Redox-flow batteries[7].

Other proposed battery systems include:

- Magnesium batteries[8]
- Calcium batteries[9]
- Al and Al-ion batteries[10]
- Anionic batteries, i.e. fluoride-ion batteries and chloride-ion batteries[11].

In addition, organic active materials[12] are included due to their potential in terms of low environmental footprint and toxicity.

Of these technologies, Li-ion, Li-metal, and Na-ion are currently the state of art. However, it is generally considered that **Li-ion cells** will outperform the other close-to-market battery technologies in the next 10-20 years[13] with Na- ion as a potential contender if the price of Li-ion battery increase and if safer low-cost Na-ion becomes available[14]. With regards to Li-metal there are several research programs worldwide (such as Battery 500, RISING II, Made in China 2025[15]) who are working to take full advantage of Li-metal anodes for commercial cells. As depicted in Figure 9 (modified from Battery 2030+) these research programs are quite ambitious, aiming for Generation 4 cells (all solid-state Li-ion/Li-metal) from around 2025.

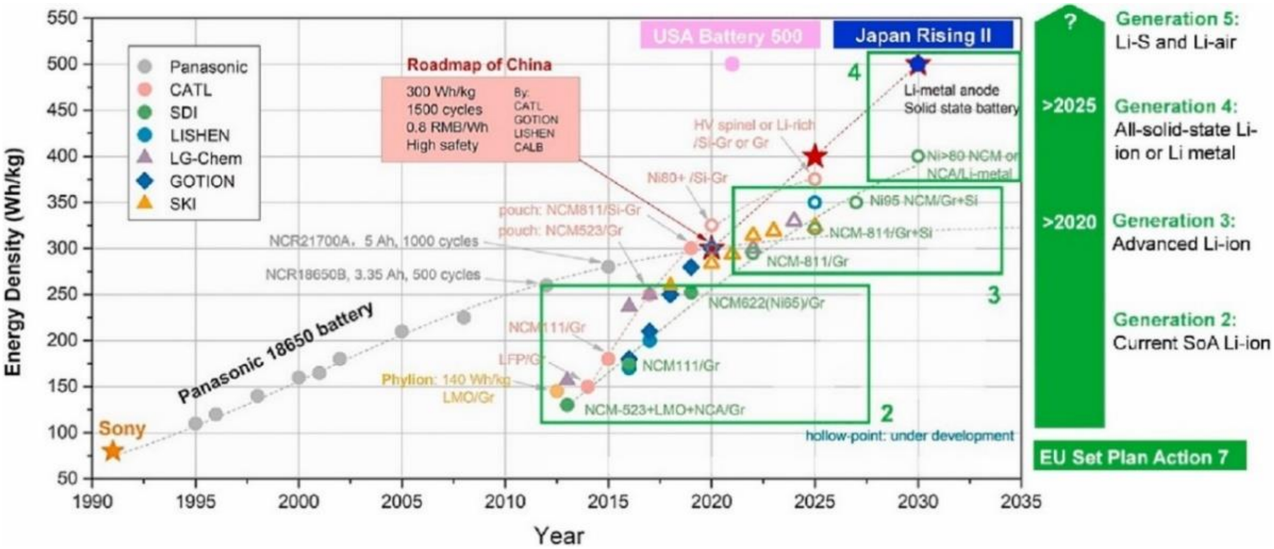

Figure 9. Roadmaps of different R&D programs worldwide[4] (modifiedfrom Battery 2030+ Roadmap[††]).

According to the road map for future battery technologies in Figure 10, we can expect several new developments with regards to cathode/anode and electrolytes. The next sections will focus on these developments.

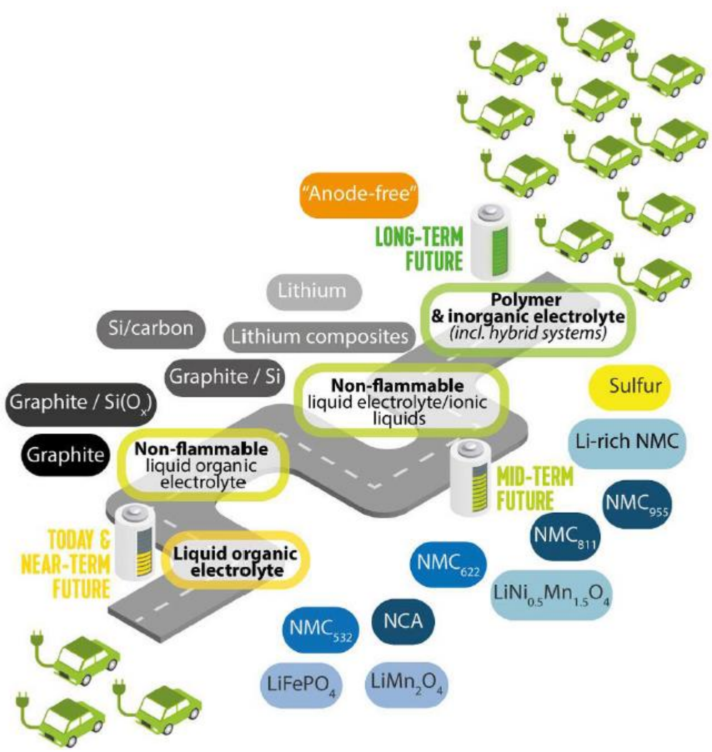

Figure 10. Roadmap for future battery technologies[13].

[††] Battery 2030+ Roadmap (diva-portal.org)

Cathodes

Figure 11 and Table 3 summarize updated predictions and selected expected developments for market shares of different cathode chemistries. These include recent reports from BNEF, Xu et al. and the Faraday institute (UK). Similar to the forecasts shown in the initial report (Figure 20), the trend towards higher-nickel chemistries continues. Minor adjustments in the trends for different NMC types have been made, further reducing market shares of lower Ni chemistries, such as NMC111. The **increase in Ni-contents** generally follows two main pathways: (i) the NMC pathway, from NMC111 towards NMC9.5.5 and (ii) the NCA approach, further increasing Ni contents in state-of-the-art NCA up to over 88%. Large uncertainties prevail regarding the future development of LFP: while earlier predictions indicated a slow but steady decrease in usage of LFP cathodes, Tesla's announcement of introducing LFP into their introductory models in China (teaming up with CATL[‡‡]) might lead to a boost in LFP usage, as indicated by Xu's LFP scenario (cf. scenario Xu1[1] in Figure 11).

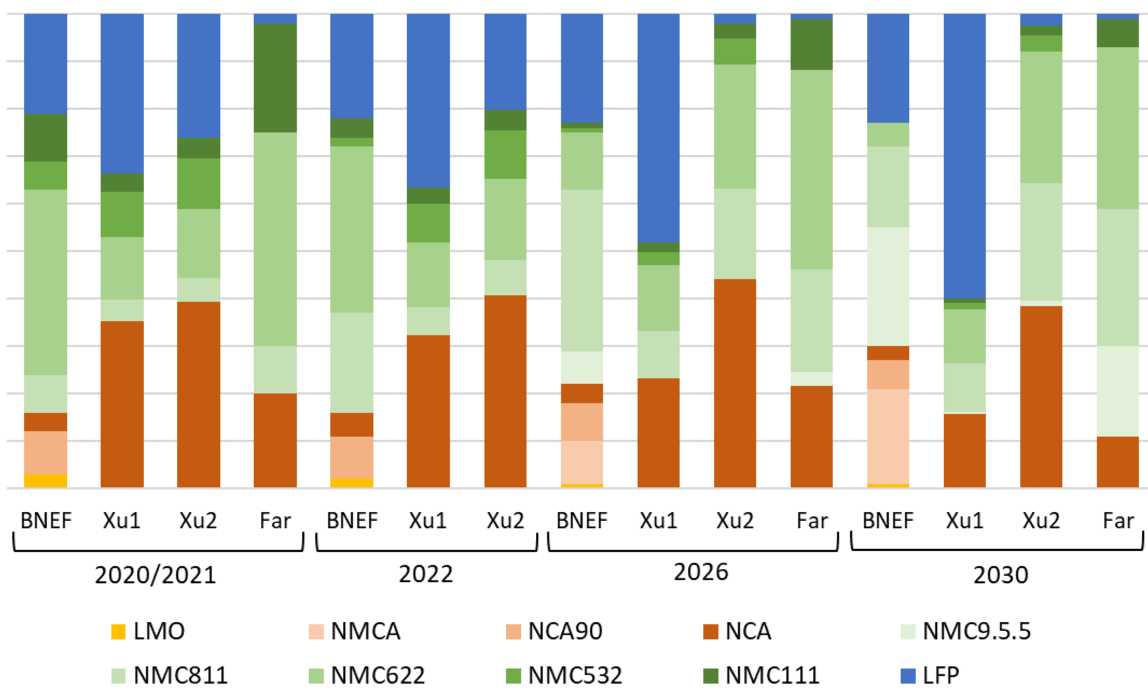

Figure 11: Expected developments of the market share of different battery chemistries. A summary combing reports from most recent reports from BNEF, Xu et al. and the Faraday institute. BNEF includes all types of batteries, while Xu and Faraday only include EV batteries. Xu1 refers to a scenario with increased focus on LFP, Xu2 to a more standard scenario.

High-Mn-cathodes. Contrasting the general high-Ni trend, Volkswagen very recently announced their intention to move towards high-manganese cathodes as their future mainstream cathode chemistry during their Power Day event in March 2021. BloombergNEF also speculated on this trend, labelling the 2010's the decade of cobalt, the decade of Ni in the 2020's, following by a potential decade of manganese in the 2030's, in a push to reduce material costs and supply constraints. Currently, the main challenge with Mn-rich cathodes is their poor cycle life and thermal stability due to the weak Mn bonding, leading to fast battery degradation. However, promising innovations happen on both, the family of layered oxides

[‡‡] https://medium.com/batterybits/the-rise-of-catl-29452bea854a

(cf. NMC type) as well as the class of 3D spinel cathodes (commonly high voltage; abbreviated LMO). The currently most promising technology on the Mn-rich front seems to be high-voltage $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO), with both, the Danish company *Haldor Topsoe* (partnering with *Morrow*, see below) and the Canadian company *Nano One* (partnering with VW since 2019), actively working on the developments of commercial industrial LNMO. Due to problems with liquid electrolytes at such high voltages, research efforts also seem to go towards the application of LNMO cathodes together with solid-state electrolytes.

Table 3: Summary of cathode trends and predictions (cf. Figure 11).

	2020/2021				2022			2026				2030			
	BNEF	Xu1	Xu2	Far	BNEF	Xu1	Xu2	BNEF	Xu1	Xu2	Far	BNEF	Xu1	Xu2	Far
LMO	3				2			1				1			
NCA90	9				9			8				6			
NCA	4	35	39	20	5	32	41	4	23	44	22	3	16	39	11
NMCA								9				20			
NMC-9.5.5								7			3	25	0	1	19
NMC-811	8	5	5	10	21	6	8	34	10	19	22	17	10	25	29
NMC-622	39	13	15	45	35	14	17	12	14	26	43	5	11	28	34
NMC-532	6	10	11		2	8	10	1	3	6			2	4	
NMC-111	10	4	4	23	4	4	4	1	2	3	11		1	2	6
LFP	21	34	26	2	22	36	20	23	48	2	1	23	60	3	1

Industry. Within 2020, we have seen the following main developments in industry:

- *SK innovation* was announced to be the first battery maker to commercialize NMC9.5.5 batteries, to be supplied to Ford F-150 electric pickup trucks, expected in 2023[§§] (benefits: longer range and shorter charging time).
- *LG Chem* are currently already producing NMC811 (supplied to Tesla Model 3 sedan manufactured in China) and have planned to produce 90% Ni content batteries with NCMA (nickel cobalt manganese aluminium) to be supplied to General Motors (*Ultium* batteries).
- *Samsung SDI* announced their Gen.5 batteries with high-Ni NCA (over 88% Ni). These have been used in power tools since 2015 but are now planned to also enter the EV market, with energy density of at least 600 Wh/L[***]. *Samsung SDI* announced a major expansion of their existing factory in Hungary (also for high-Ni NCA), announced to start production in the second half of 2021, gradually increasing production to 18 million cells per month (no capacities mentioned), and supply to EVs from BMW, Audi, VW.
- *Morrow* recently announced to team up with the Danish company *Haldor Topsoe*, pilot facility to produce entirely cobalt-free LNMO ($LiNi_{0.5}Mn_{1.5}O_4$) cells[†††]. As opposed to the 2D layered structures in the NMC group, LNMO has a 3D (spinel) structure, offering the potential for high discharge/charging rates, besides the advantages of high working potentials (4.7 V *vs* Li/Li^+), high

[§§] http://www.koreaherald.com/view.php?ud=20200810000683
[***] https://www.samsungsdi.com/column/technology/detail/56458.html?listType=gallery
[†††] https://kommunikasjon.ntb.no/pressemelding/morrow-batteries-partners-with-haldor-topsoe-to-establish-cobalt-free-cathode-pilot-production-in-norway?publisherId=16388593&releaseId=17899642

energy densities and reduced cost (about 20% compared to the tri-metal cathodes such as NCA and NMC).

Research. The trend towards a reduction of Cobalt in cathodes is also observed at research level.

- *High-nickel NMA* (89mol% Ni, Mn, Al)[16], is a novel, Co-free, high-Ni cathode material, composed of 89 mol% Ni, Mn and Al. First preliminary studies indicate similar or even better electrochemical performance when benchmarked against NCA and NMC. Similar synthesis routines are set to allow for easy commercialisation.
- *NFA-batteries*. Still at the early stages of research, Oak Ridge National Laboratories recently presented a new viable candidate for Co-free LIBs: so-called NFA-batteries with general formula $LiNi_xFe_yAl_zO_2$ ($x + y + z = 1$)[17]. Initial tests show specific capacities of around 200 mAh/g, reasonable rate capacity and 80% capacity retention after 100 cycles.
- *Single crystal cathodes*: promising for high energy density and long-life cells[18].

Anodes

In our previous report, as well as recent literature[19], Graphite was still considered to be the main anode material for the foreseeable future. This is still the case, but as we see in Figure 10, there is a transition towards incorporating more and more silicon to increase the capacity in the near future, while moving towards lithium metal and anode free on the long term. For fast charging, $Li_4Ti_5O_{12}$ (LTO), is generally considered a safer anode option for high power batteries[19]. LTO was well covered in the previous report, but LTO might have a contender $Li_3V_2O_5$, who with its lower voltage vs. Li can provide higher energy densities than LTO[20].

Silicon and silicon/carbon composites.

Si and SiO_x has been substantially studied for the past 20 years due to their ability to offer much higher specific capacities compared to carbonaceous anodes[21]. Si is also abundant, cheap, and non-toxic. The main disadvantage with alloying materials such as Si is **poor cyclability** due to large volume expansion (280%) during lithiation. Incorporation of oxygen can improve the cyclability but there is a trade-off between high stability and initial CE (ICE)[22]. In this regard **pre-lithiation** of the anodes is often proposed as solution account for the lost lithium during the formation cycles[23].

One of the biggest challenges for alloying materials is that many of the studies use low areal loadings and densities, which effectively results in lower volumetric capacities compared to graphite[19]. The areal capacities must be sufficiently high (> 3 mAh/cm^2) to get commercially competitive performance.

Improvements in energy densities are achievable by increasing the anode capacities through incorporation of Si/SiO/SiC composite electrodes, as seen in Figure 12a, and it is anticipated that energy densities of 800-1000 Wh/L can be reached with Si/graphite/carbon composites[22]. However, the massive volume expansions during cycling puts design limitations as the porosity and electrode density changes considerable during lithiation (Figure 12b). The maximum gravimetric and volumetric capacity of Si based electrodes capable of 2.0 C charging rates was found to be 468 Ah/kg and 1418 Ah/L[24]. This is far less than the theoretical capacities of Si, but still a massive improvement compared to state-of-the-art graphite electrodes.

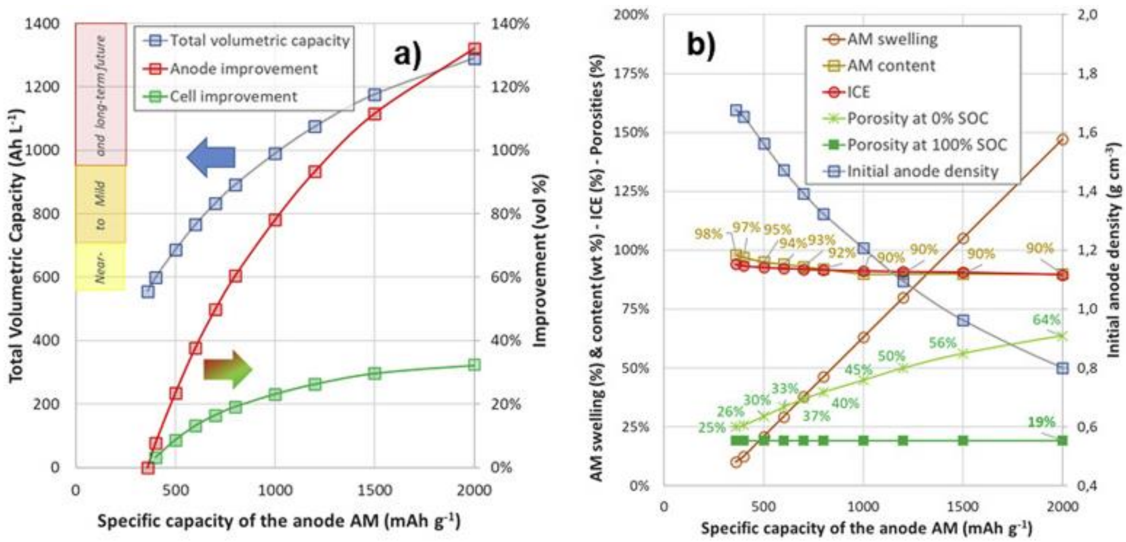

Figure 12. a) Potential improvements in volumeric capacities as a function of improvementes in specfific capacity of the anode, b) Theoretical estimation of the effect of active material (AM) capacity on electrode denisty, porosity swelling at different state of charge.

Li metal batteries (Li-sulfur/ Li-O_2/anode free)

Further improvements are expected to be achieved using Li- metal anodes in combination with sulfur cathodes, oxygen () and/or anode free design. There are two main approaches to stabilize lithium metal, Figure 13[4]. Either by modifying the SEI in liquid electrolytes[25], or by moving towards **solid state electrolytes (SSE)**[26].

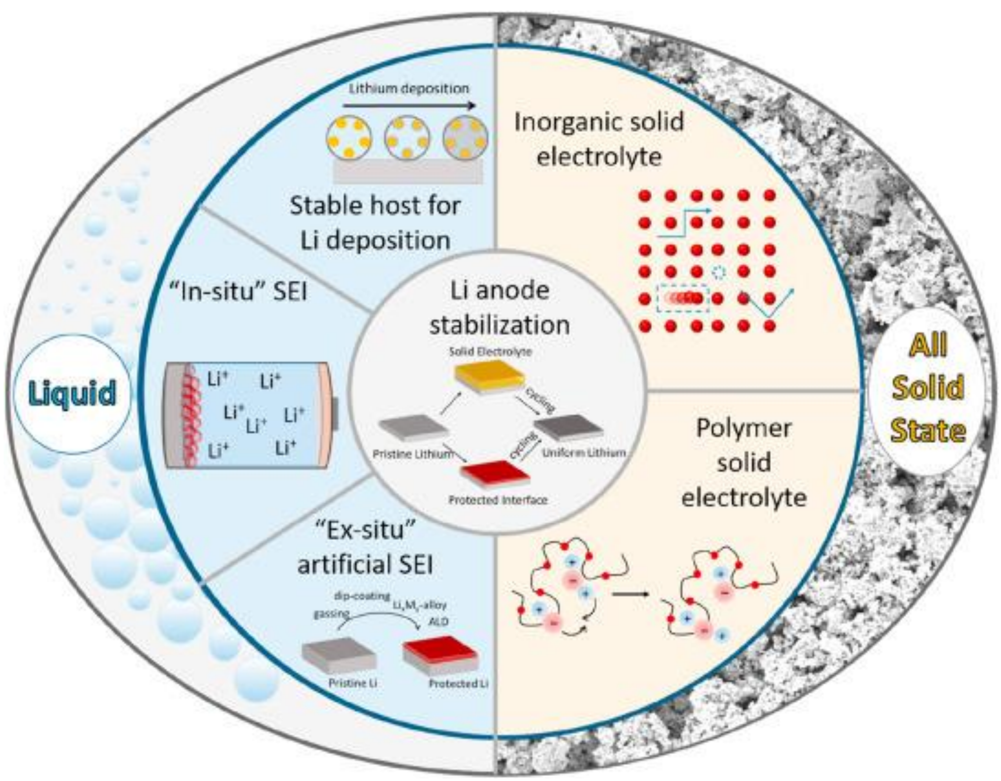

Figure 13 Paths towards stabilizing Li-metal[4].

Solid state electrolytes are usually divided into *inorganic solid electrolyte (ISE)* and p*olymer solid electrolytes (SPE*). For Lithium metal ASSBs (all solid-state batteries), ISEs are considered one of the most promising energy storage technologies for automotive and stationary applications[4]. Table 4 summarizes the current status for lithium metal batteries and compares them with EUs goal for 2030 in terms of energy density, power density and cycle life.

Table 4 Summary of the status of Li-metal batteries as compared to the set goals of the EU[4].

SET Plan Targets 2030 (at cell level)	**Current status**	**Li Metal Batteries**			
		Generation 4: ASSB		**Generation 5: conversion cathodes**	
		Inorganic	**polymeric**	**Li-S**	**Li-air**
	TRL	4-6	commercial	5-7	1-4
Energy **>400 Wh/kg** **>750 Wh/L**		450 Wh/kg 900 Wh/L	**Estimated (Lab scale)** 300 Wh/kg 500-600 Wh/L **Practical (EVs)** 100-180 Wh/kg 100 Wh/L	>450 Wh/kg 700 Wh/L	Theoretical limits 1700 Wh/kg 1850 Wh/L
	Limiting factor	ISE stability towards high voltage cathodes	Operating temperature > 60 ºC SPE stability towards high voltage cathodes	Electrolyte excess required	Li_2O_2 deposition and dissolution mechanism
	Suggested measures	Develop more effective coatings	Electrolyte additives New cell chemistries	New electrolytes Improved electrolyte anode interphase	New electrolytes/additives based on mechanistic studies
Power **> 700 Wh/kg** **>1500 Wh/L** **Charge time (min):12**		500 W/kg 1000 W/L	**Practical (EV)** <200 W/kg <200 W/L	500 W/kg 1000 W/L	N/A
	Limiting factor	High cell impedance	Low Li+ transference numnber	Cathode conversion kinetics Electrolyte resistance	Li_2O_2 deposition and dissolution mechanism
	Suggested measures	Reduction of SE thickness	New electrolyte formulations	Improved electrolytes Electrode design	New electrolyte/additives based on mechanistic studies
Cycle Life (to 80 % DOD)		1000	Ca. 1300	<1000 (<100 for high energy cells)	N/A

BEV:2000	**Limiting factor**	Contact issues at interfaces	Stability of electrode/electrolyte interphase	Electrolyte	Parasitic chemistry at cathode
Stationary: 10000		Dendrite growth		Anode depletion	
	Suggested measures	Stable interlayers (hybrid)	Electrolyte additives	New electrolytes	Detailed understanding of O_2 formation mechanisms
		Highly dense SE	New electrolyte formulations0	Improved electrolyte anode interphase	New electrolytes/additives based on mechanistic studies

As shown in Table 4, polymeric solid-state electrolytes have already reached commercial technology readiness level (TRL). However, it is expected that inorganic electrolytes will eventually take over due to its lower operating temperature and higher energy and power densities.

Industry. There are already some commercial and planned developments in the **industry** with regards to lithium metal batteries. Among these are:

- *OXIS energy: Commercial Li/S producer*
- *Morrow:* Planned Gigafactory in Norway using Li/S technology
- *GM motors* partner with *solid energy systems (SES)* on anode free lithium metal *battery*
- *Toyota.* Planning to unveil their all-solid-state EV in 2021.

Research. The following **research** areas are expected with regards to *anodes* and *electrolytes* to reach the EU goals in Table 4.

- *Higher Si-content anodes*: anode architecture, binder, coatings, polymer
- *Solid state electrolyte (ISE)*: Reduce thickness/interfacial impedance and stability towards high voltage cathodes.
- *Li/S*: Reduce electrolyte amount ($LiNO_3$ consumption), preventing shuttle mechanisms, encapsulation/electrode architecture.
- Li/O_2: Development of new electrolytes and additives based on mechanistic studies.

Battery cell production

Battery manufacturing capacity in Europe is currently around 26 GWh, until 2030 it is expected to increase to a total of 500 GWh[‡‡‡]. The European automotive industry remains the major driving force behind the growing market and several of the new gigafactories are established as strategic alliances between original equipment manufacturers (OEM) and battery producers. New developments also include leading Asian and US companies, such as Tesla, LG Chem and CATL, who are following their European customers and establishing production capacity in Europe. Figure 14 illustrates the map of European battery cell production capacity that is continuously expanding. BMI foresees that Europe will increase its share to 16 % of the global battery market by 2029 (expected to be 2.5 TWh in 2030), compared to just 6 % of today's

‡‡‡ https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf

market[§§§], while Wood Mackenzie's latest report estimates that Europe will ramp up to even 25% of the global capacity in 2030, with the global lithium-ion cell manufacturing capacity expected to reach 1.3 TWh by 2030[****].

In the recent analysis by CIC energiGUNE (Figure 14), the four Norwegian initiatives are included, as well as new plans in France and Spain. The situation is changing rapidly, and the map will shortly have needs of new updates.

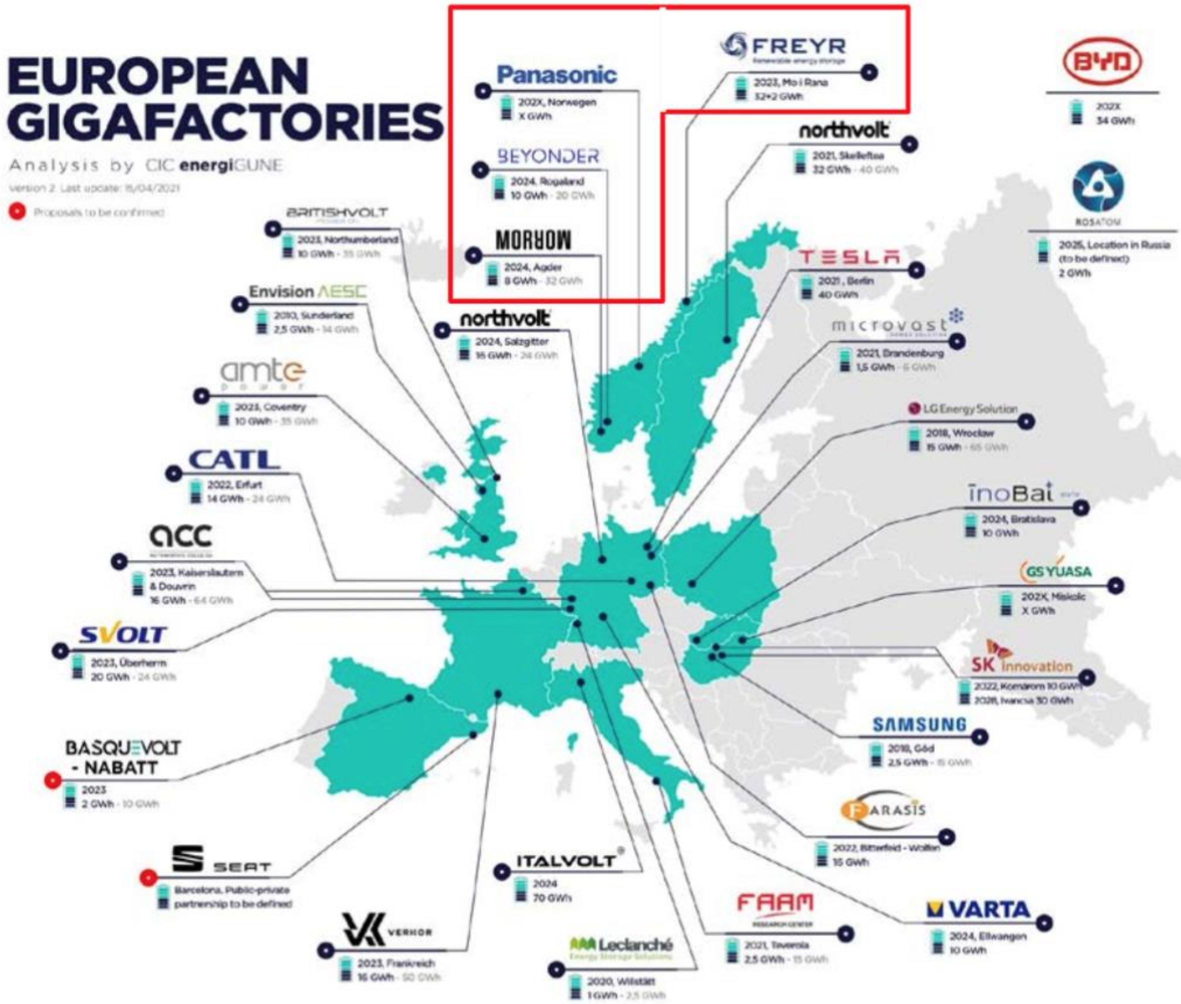

Figure 14: Map of European battery cell production capacity (CIC energiGUNE).

§§§ Benchmark Minerals, May 2020
**** https://www.miningreview.com/battery-metals/lithium-ion-cell-capacity-to-quadruple-to-1-3-twh-by-2030/

Batteries: From cell to system level

The most common cell types are shown in Figure 15.

Figure 15. Typical cell types for Li-ion batteries. From left to right; Pouch cell, Cylindrical and Prismatic cell[27].

These are p*ouch cell, cylindrical cell, and prismatic cell.* There is so far no *one* cell type which dominates the market as they are all used by different OEMs[27]. Moving from cell level to system level, where you must account for additional weight gains in cooling system, casings, battery management systems (BMS) etc., can significantly reduce the resulting energy density. As seen in Figure 16, the energy densities moving from cell level to system level decreases for all cell types. The cylindrical cells generally outperform pouch cell and prismatic cells on a *cell level*, but suffers from a higher loss towards system level, compared to pouch and prismatic, due to less optimal packing density.

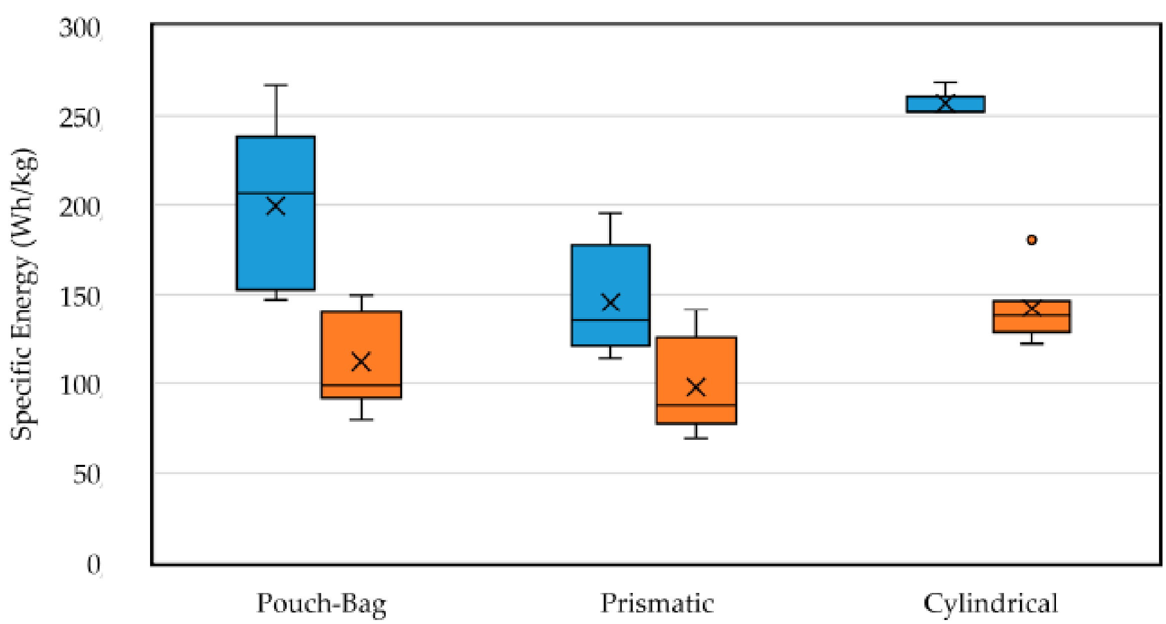

Figure 16. Cell type and energy density on cell level (blue) and system level (orange) from 25 assessed vehicles[27].

The materials encapsulating the cells, modules and systems can vary depending on application, design, and cooling method. The Battery Performance and Cost model (BatPaC) developed at Argonne National Laboratory for lithium-ion battery[28] is a useful tool to estimate the cost of the designed battery, accounting for every step in the lithium-ion battery manufacturing process. From their experience the exact design of the battery does not have an important effect on the *cost* for a set cell chemistry system compared to the amount of active material, capacity, and electrode area. However, as seen in Figure 16, there is an impact of the weight of the "dead" cell/module/system components on the overall energy density. The stiff-pouch containment used in BatPaC uses a tri-layer of polyethylene terephthalate (PEP), 0.1-mm aluminum for stiffness and an inner layer of polypropylene (PP), as the cell housing materials, and a 0.5-mm thick aluminum for the module casings and is assumed to provide a good reference point for estimation. However, in the transition from cell to system level there is significant room for improvement with regards to optimizing packaging [27]. Moving from cell level to module/system also requires some material for the Li-ion interconnections. Table 5. Overview of materials used for Li-ion interconnection[29] provides a good overview of the most used materials for Li-ion interconnections for the different cell systems.

Table 5. Overview of materials used for Li-ion interconnection[29].

	Cylindrical cell	Pouch cell	Prismatic cell
Housing	Nickel-plated steel, steel, aluminium	-	Steel, aluminium
Negative tap/terminal	Nickel-plated steel, steel, aluminium, nickel copper	Copper, nickel plated copper	Copper, aluminium, nickel
Positive tap/terminal	Nickel-plated steel, steel,aluminium	Aluminium	Aluminium, nickel
Collector-, bus-bar, interconnector	Copper, nickel, nickel-plated steel, nickel-plated copper, aluminium		

A lot of innovative effort has been going into the actual cell and pack design as well as new manufacturing technologies. Examples include:

- 24M technology (Freyr)
- Blade battery design by BYD: new battery pack design, leading to improved safety, cycle life and energy density for LFP based battery, while lowering the cost[††††]
- Dry coating (Tesla)
- Tabless design (Tesla)

Recycling and reuse

The topic of reuse of batteries (**second life**) is becoming increasingly interesting to Norwegian industry and research partners, and several of the participants in the BATMAN project is currently involved in recently started projects focusing on second life use of batteries. There are several **start-up companies** (Ecostor, RePack, Hagal, Eaton) focusing on second use of EV batteries and their initial experience along with the outcomes of the researcher projects will provide a good basis for understanding the role of second life batteries in the **Norwegian energy system**.

The **2ND LIFE**[‡‡‡‡] project, a RCN-funded project coordinated by IFE will identify and quantify obstacles and opportunities for the Norwegian 2nd life battery market's ability to contribute to the European strive towards a carbon neutral economy. The project will develop statistics of End-of-1st life batteries in Norway, understand the battery safety, develop models for prediction of performance for 2nd life batteries

†††† https://medium.com/batterybits/a-sharp-contender-byds-blade-battery-ced2ef1dc8f8
‡‡‡‡ KPN-project (2021-2024) RCN-no: 320760

as well as quantifying the overall impact on environment through LCA analysis. Partners in the project include IFE, FFI, NTNU, UiA, Hydro, Equinor, Ecostor, Batteriretur and Corvus.

The regional research fund in Agder has also recently funded the **ELAG**[§§§§] project which is coordinated by UiA and involves industry partners such as BTG, Pixii, Greenstat Energy, Elkem, Hydro, Green Waves and Batteriretur. The project will focus on battery characterisation, automated processing of used batteries, use of second life batteries in energy storage systems to support the electrification of society and strengthening the sustainability and circularity within the Norwegian battery value chain.

The main motivation for the secondary use of EV batteries is the growth in **stationary storage battery** application. The important parameters and preferred chemistries of stationary storage batteries is described in the Segment chapter.

When it comes to recycling of battery material, there has also been recent developments within Norway that are worth mentioning. **Hydrovolt** was established in 2020 as a joint venture between Hydro and the battery producer Northvolt in Sweden and will harness synergies between the battery and the aluminium industries. In Fredrikstad, the first electric car battery recycling plant will be built in 2021 and it will be automated and designed for **crushing and sorting batteries**. The capacity will be large enough to handle not only spent EV batteries from Norway, but also across Scandinavia. Hydro can reuse the aluminium from the batteries, whereas the **black mass** (containing lithium, manganese and cobalt) can be reused by Northvolt or sold to other parties. [*****]

Recycling technologies

Alongside the continuously growing demand for LIBs, the amount of LIBs available for recycling will also increase significantly. LIB recycling will play a crucial part in the reduction of primary material production. As of today, the main challenges with LIB recycling still lie in the large variety and complexity of LIBs in shape, size and chemistries. Efficient LIB recycling is thus still a big challenge, involving complex separation and purification processes[30], and the necessity of improving recycling technologies is clearly recognised by the scientific community[31]. A general overview on the main LIB recycling technologies is given in the original report. Current commercial recycling technologies fall into three categories: (i) pyrometallurgical recycling (ii) hydrometallurgical recycling and (iii) mechanical or physical recycling, as well as combinations of these. A generalized recycling loop is illustrated in Figure 17.

Additionally, recycling can be classified into closed-loop recycling, in which pyrometallurgical processing is followed by hydrometallurgical processing, resulting in metal salts, and direct recycling, aiming at recovering the materials directly by keeping their chemical structures[1]. Direct recycling offers numerous advantages but is still at its early development stages. Xu *et al.*[1] consider three different potential recycling scenarios (pyrometallurgical, hydrometallurgical and direct) for NMC/NCA and LFP batteries. Up until 2050 they predict that recycling can reduce the cumulative material demand for Li, Co and Ni by around 20-40% (for details see [1] or respective materials section above). Once a steady state has been reached, i.e. the battery stock of a saturated battery market has built up, secondary materials could take up to 90% (recycling efficiency) of the materials share in new batteries.

[§§§§] RFF project at UiA https://www.uia.no/en/news/giving-used-electric-vehicle-batteries-a-new-life
[*****] https://hydrovolt.com/

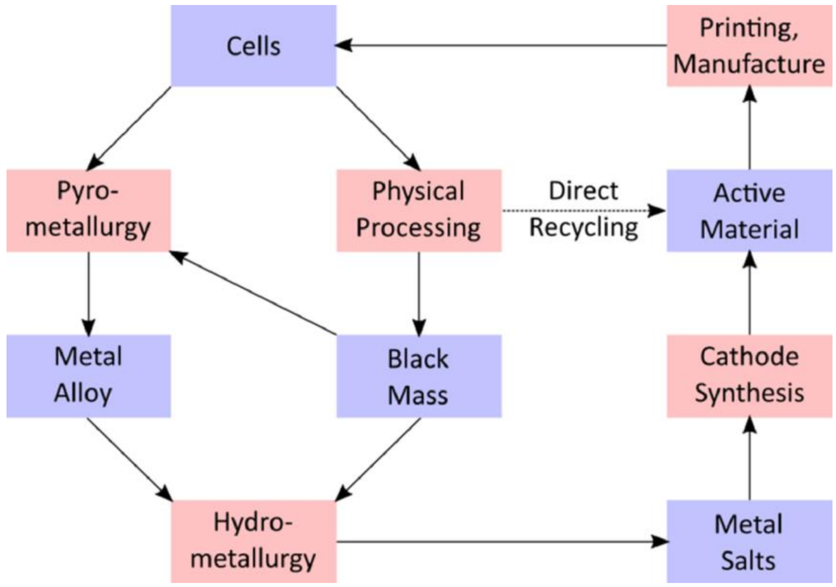

Figure 17: Generalised recycling loop with materials shown in blue, processes in red [32].

Figure 18 gives an overview of predicted closed-loop recycling potentials up to 2050, including predictions for a possible reduction/time delay of incoming batteries due to 2nd life applications[1].

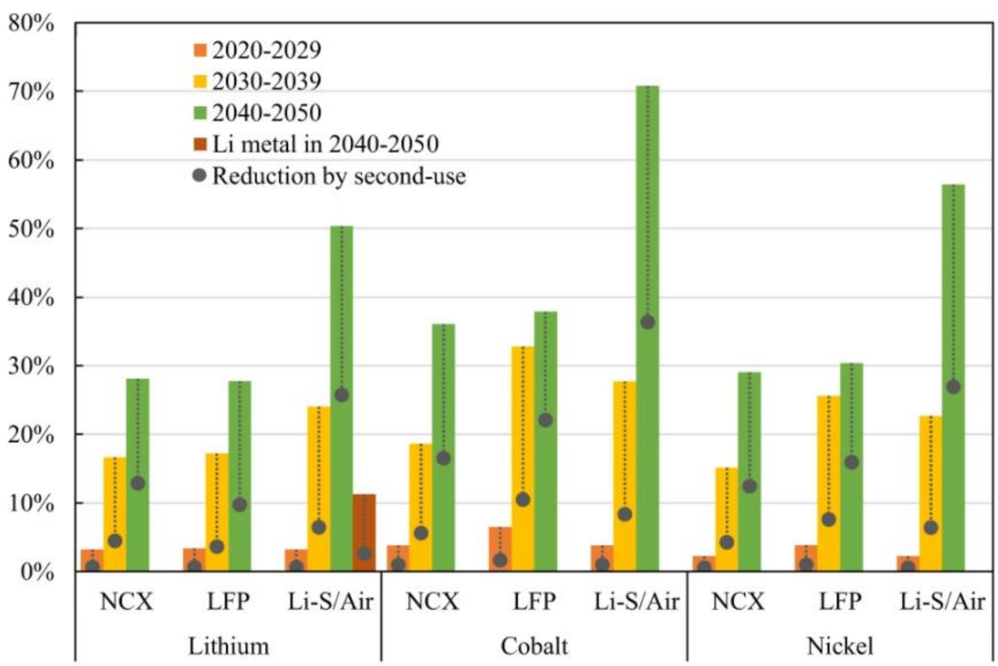

Figure 18: Closed loop recycling potential of critical battery materials[1].

Regional trends: Europe vs USA vs Asia

This section gives a brief overview on different expected trends in different areas of the world. For more details see the respective references.

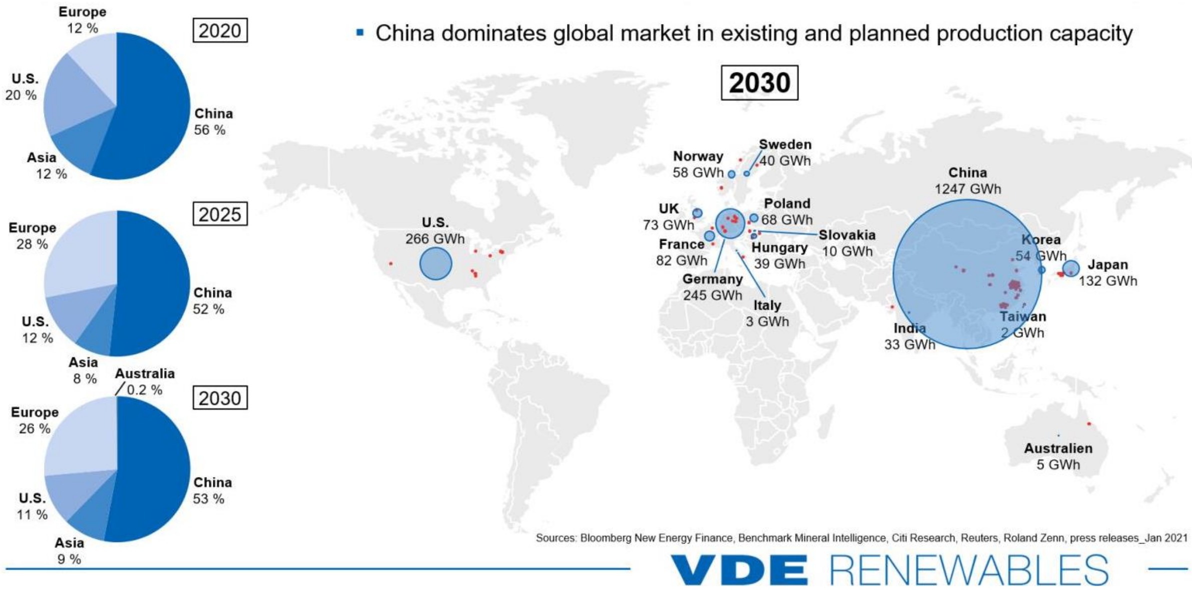

Figure 19: Gigafactory capacities for LIB cells by region (Source: Bloomberg New Energy Finance, BMI, press release Jan 2021)[†††††].

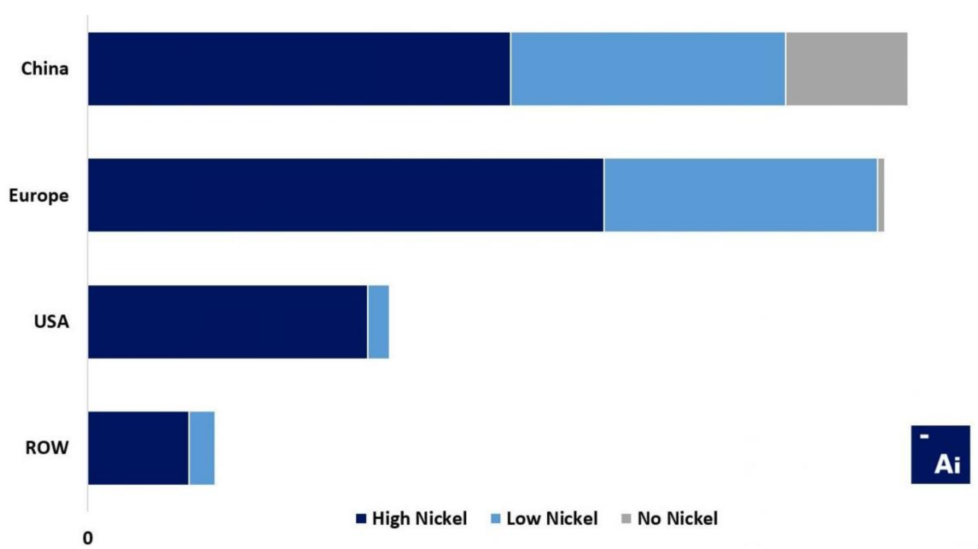

Figure 20: Passenger EV battery capacity (GWh) deployed onto roads in 2020. Chart considers passenger BEV and PHEV capacity deployed onto roads in 2020 and excludes any additional battery capacity in sales channels and pack assembly lines. High Nickel = NCA, NMC 6 to 8 series, Low Nickel = NMC 1 to 5 series, No Nickel = LFP, LMO.[‡‡‡‡‡]

[†††††] https://www.linkedin.com/posts/dr-jochen-m%C3%A4hli%C3%9F-380a9716b_gigafactories-lithiumion-cells-activity-6753324720826920960-PEv9/

[‡‡‡‡‡] https://www.adamasintel.com/high-nickel-cathodes-dominate-passenger-ev-market-2020/

Segments

As summarized in the introduction, the largest contributor to LIB growth is the EV industry, directly followed by stationary energy storage (ESS). Electrification in maritime industry and public transport (electric busses) is steadily increasing, however, still represents a minor part compared to EV+ESS.

Stationary Energy Storage (ESS)

As stationary energy storage is becoming the second largest segment contributing to the LIB growth, the battery chemistry and technology will play a larger role. It is anticipated that end-of life (EoL) EV batteries may experience a **second use** for less demanding applications such as stationary energy storage, as the batteries often have a remaining capacity of around 70-80 %. There are still some technical barriers to overcome (the performance and safety of repurposed batteries) as well as economic uncertainty (cost of repurposing including disassembly, testing, and repackaging) before second-use applications will become commonly accepted. Depending on the battery chemistry, state-of-health and the intended application a variety of second life applications will exist. For example, LFP batteries are assumed to have 100 % second-use rate due to the long cycle life of LFP. For the rest of the battery chemistries, a 50 % second-use rate before 2020 is assumed, rising to 70 % during 2020-2050 due to improved technical lifespan of EV batteries[1]. Also noteworthy, is the assumption that **battery modules** are assumed at 100 % reuse rate, while pack components enter recycling directly. The secondary life as ESS is expected to be on average 10 years, depending on the type of application. Many of the new Gigafactory industries point to **LFP** as a good candidate for ESS units, due to the long lifetime of the material.[§§§§§]

As the cost and lifetime are the two major drivers within the stationary storage segments, there is also extensive research on new chemistries and also other types of batteries than LIBs that could be suitable for stationary storage applications. These include for example **sodium-ion** and sodium-metal batteries, although there is some uncertainty in how fast Na-based materials will be commercially available and how price-competitive it will be compared with the rapidly reducing cost of LiBs.

[§§§§§] Freyr presentation at MoZEES Battery Days among others

Summary & Outlook

This report should be read together with the first report from IFE, LIB technology mapping report, to get a complete overview of the current and future trends withing the lithium-ion battery chemistry.

The market for Li-ion batteries is rapidly increasing, mainly due to the expansion of the EV market, coupled with lower prices (reduced to just over 100 /kWh in 2020), ensuring a growing demand for Li-ion batteries across all sectors. The growing market is exemplified by all the new emerging battery manufactures in Norway (FREYR, MORROW) and rest of Europe.

As the need for batteries is growing, so does the need for raw material. Specifically, Co, Li and to some extent Ni are critical raw materials which might be challenging to obtain with mining efforts alone. Recycling will therefore be necessary to meet these demands and we are already seeing promising initiative across Europe, but also in Norway in terms of recycling and second life use of batteries.

For the cell chemistries, the generally trend is moving towards reduced Co content in the cathode and more silicon together with graphite in the anode. The electrolyte is currently mostly liquid, but solid-state electrolytes have received much more focus due to its potential to enable the next leap in energy densities through Li-metal /Li-Sulphur batteries. Standard Li-ion batteries will still dominate the market for the foreseeable future, but we see more and more focus on next generation technologies, and it is expected that these new technologies will see a larger market share from 2025 towards 2030.

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References

1. Xu, C.; Dai, Q.; Gaines, L.; Hu, M.; Tukker, A.; Steubing, B., Future material demand for automotive lithium-based batteries. *Communications Materials* **2020,** *1* (1).
2. Li, J.; Passerini, S., Introduction to the special Issue: Focus review - New and emerging battery technologies. *Journal of Power Sources* **2021,** *484*.
3. *Report on the Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe*; COM (2019) 640 final, 176 final, 9.4.2019.
4. Varzi, A.; Thanner, K.; Scipioni, R.; Di Lecce, D.; Hassoun, J.; Dörfler, S.; Altheus, H.; Kaskel, S.; Prehal, C.; Freunberger, S. A., Current status and future perspectives of lithium metal batteries. *Journal of Power Sources* **2020,** *480*.
5. Hasa, I.; Mariyappan, S.; Saurel, D.; Adelhelm, P.; Koposov, A. Y.; Masquelier, C.; Croguennec, L.; Casas-Cabanas, M., Challenges of today for Na-based batteries of the future: From materials to cell metrics. *Journal of Power Sources* **2021,** *482*.
6. Borchers, N.; Clark, S.; Horstmann, B.; Jayasayee, K.; Juel, M.; Stevens, P., Innovative zinc-based batteries. *Journal of Power Sources* **2021,** *484*.
7. Sánchez-Díez, E.; Ventosa, E.; Guarnieri, M.; Trovò, A.; Flox, C.; Marcilla, R.; Soavi, F.; Mazur, P.; Aranzabe, E.; Ferret, R., Redox flow batteries: Status and perspective towards sustainable stationary energy storage. *Journal of Power Sources* **2021,** *481*.
8. Dominko, R.; Bitenc, J.; Berthelot, R.; Gauthier, M.; Pagot, G.; Di Noto, V., Magnesium batteries: Current picture and missing pieces of the puzzle. *Journal of Power Sources* **2020,** *478*.
9. Stievano, L.; de Meatza, I.; Bitenc, J.; Cavallo, C.; Brutti, S.; Navarra, M. A., Emerging calcium batteries. *Journal of Power Sources* **2021,** *482*.
10. Elia, G. A.; Kravchyk, K. V.; Kovalenko, M. V.; Chacón, J.; Holland, A.; Wills, R. G. A., An overview and prospective on Al and Al-ion battery technologies. *Journal of Power Sources* **2021,** *481*.
11. Karkera, G.; Reddy, M. A.; Fichtner, M., Recent developments and future perspectives of anionic batteries. *Journal of Power Sources* **2021,** *481*.
12. Esser, B.; Dolhem, F.; Becuwe, M.; Poizot, P.; Vlad, A.; Brandell, D., A perspective on organic electrode materials and technologies for next generation batteries. *Journal of Power Sources* **2021,** *482*.
13. Marinaro, M.; Bresser, D.; Beyer, E.; Faguy, P.; Hosoi, K.; Li, H.; Sakovica, J.; Amine, K.; Wohlfahrt-Mehrens, M.; Passerini, S., Bringing forward the development of battery cells for automotive applications: Perspective of R&D activities in China, Japan, the EU and the USA. *Journal of Power Sources* **2020,** *459*.
14. Vaalma, C.; Buchholz, D.; Weil, M.; Passerini, S., A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials* **2018,** *3* (4).
15. Lu, Y.; Rong, X.; Hu, Y.-S.; Chen, L.; Li, H., Research and development of advanced battery materials in China. *Energy Storage Materials* **2019,** *23*, 144-153.
16. Li, W.; Lee, S.; Manthiram, A., High-Nickel NMA: A Cobalt-Free Alternative to NMC and NCA Cathodes for Lithium-Ion Batteries. *Adv Mater* **2020,** *32* (33), e2002718.
17. Muralidharan, N.; Essehli, R.; Hermann, R. P.; Amin, R.; Jafta, C.; Zhang, J.; Liu, J.; Du, Z.; Meyer, H. M.; Self, E.; Nanda, J.; Belharouak, I., Lithium Iron Aluminum Nickelate, $LiNi_xFe_yAl_zO_2$ -New Sustainable Cathodes for Next-Generation Cobalt-Free Li-Ion Batteries. *Advanced Materials* **2020,** *32* (34), e2002960.
18. Liu, Y.; Harlow, J.; Dahn, J., Microstructural Observations of “Single Crystal” Positive Electrode Materials Before and After Long Term Cycling by Cross-section Scanning Electron Microscopy. *J Electrochem Soc* **2020,** *167* (2).
19. Armand, M.; Axmann, P.; Bresser, D.; Copley, M.; Edström, K.; Ekberg, C.; Guyomard, D.; Lestriez, B.; Novák, P.; Petranikova, M.; Porcher, W.; Trabesinger, S.; Wohlfahrt-Mehrens, M.; Zhang, H., Lithium-ion batteries – Current state of the art and anticipated developments. *Journal of Power Sources* **2020,** *479*.

20. Liu, H.; Zhu, Z.; Yan, Q.; Yu, S.; He, X.; Chen, Y.; Zhang, R.; Ma, L.; Liu, T.; Li, M.; Lin, R.; Chen, Y.; Li, Y.; Xing, X.; Choi, Y.; Gao, L.; Cho, H. S.; An, K.; Feng, J.; Kostecki, R.; Amine, K.; Wu, T.; Lu, J.; Xin, H. L.; Ong, S. P.; Liu, P., A disordered rock salt anode for fast-charging lithium-ion batteries. *Nature* **2020,** *585* (7823), 63-67.

21. Zuo, X.; Zhu, J.; Müller-Buschbaum, P.; Cheng, Y.-J., Silicon based lithium-ion battery anodes: A chronicle perspective review. *Nano Energy* **2017,** *31*, 113-143.

22. Reynier, Y.; Vincens, C.; Leys, C.; Amestoy, B.; Mayousse, E.; Chavillon, B.; Blanc, L.; Gutel, E.; Porcher, W.; Hirose, T.; Matsui, C., Practical implementation of Li doped SiO in high energy density 21700 cell. *Journal of Power Sources* **2020,** *450*.

23. Aravindan, V.; Lee, Y.-S.; Madhavi, S., Best Practices for Mitigating Irreversible Capacity Loss of Negative Electrodes in Li-Ion Batteries. *Advanced Energy Materials* **2017,** *7* (17).

24. Heubner, C.; Langklotz, U.; Michaelis, A., Theoretical optimization of electrode design parameters of Si based anodes for lithium-ion batteries. *Journal of Energy Storage* **2018,** *15*, 181-190.

25. Wang, D.; Zhang, W.; Zheng, W.; Cui, X.; Rojo, T.; Zhang, Q., Towards High-Safe Lithium Metal Anodes: Suppressing Lithium Dendrites via Tuning Surface Energy. *Adv Sci (Weinh)* **2017,** *4* (1), 1600168.

26. Lin, D.; Liu, Y.; Cui, Y., Reviving the lithium metal anode for high-energy batteries. *Nat Nanotechnol* **2017,** *12* (3), 194-206.

27. Löbberding, H.; Wessel, S.; Offermanns, C.; Kehrer, M.; Rother, J.; Heimes, H.; Kampker, A., From Cell to Battery System in BEVs: Analysis of System Packing Efficiency and Cell Types. *World Electric Vehicle Journal* **2020,** *11* (4).

28. Nelson, P. A.; Ahmed, S.; Gallagher, K. G.; Dees, D. W. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles*; ANL/CSE-19/2, 150624; United States, 2019-03-01, 2019.

29. Zwicker, M. F. R.; Moghadam, M.; Zhang, W.; Nielsen, C. V., Automotive battery pack manufacturing – a review of battery to tab joining. *Journal of Advanced Joining Processes* **2020,** *1*.

30. Ma, J.; Li, Y.; Grundish, N. S.; Goodenough, J. B.; Chen, Y.; Guo, L.; Peng, Z.; Qi, X.; Yang, F.; Qie, L.; Wang, C.-A.; Huang, B.; Huang, Z.; Chen, L.; Su, D.; Wang, G.; Peng, X.; Chen, Z.; Yang, J.; He, S.; Zhang, X.; Yu, H.; Fu, C.; Jiang, M.; Deng, W.; Sun, C.-F.; Pan, Q.; Tang, Y.; Li, X.; Ji, X.; Wan, F.; Niu, Z.; Lian, F.; Wang, C.; Wallace, G. G.; Fan, M.; Meng, Q.; Xin, S.; Guo, Y.-G.; Wan, L.-J., The 2021 battery technology roadmap. *Journal of Physics D: Applied Physics* **2021,** *54* (18).

31. Beaudet, A.; Larouche, F.; Amouzegar, K.; Bouchard, P.; Zaghib, K., Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials. *Sustainability* **2020,** *12* (14).

32. Sommerville, R.; Zhu, P.; Rajaeifar, M. A.; Heidrich, O.; Goodship, V.; Kendrick, E., A qualitative assessment of lithium ion battery recycling processes. *Resources, Conservation and Recycling* **2021,** *165*.