Electronic Devices & Networks Annex EDNA

Emerging Battery Technologies

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Emerging Battery Technologies

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Report Prepared for IEA 4E EDNA by Viegand Maagøe

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Electronic Devices & Networks Annex
EDNA

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP), has been supporting governments to co-ordinate effective energy efficiency policies since 2008.

Fifteen countries have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds, which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are: Australia, Austria, Canada, China, Denmark, the European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

Further information on the 4E TCP is available from: **www.iea-4e.org**

The EDNA Annex (Electronic Devices and Networks Annex) of the 4E TCP is focussed on a horizontal subset of energy using equipment and systems - those which are able to be connected via a communications network. The objective of EDNA is to provide technical analysis and policy guidance to members and other governments aimed at improving the energy efficiency of connected devices and the systems in which they operate.

EDNA is focussed on the energy consumption of network connected devices, on the increased energy consumption that results from devices becoming network connected, and on system energy efficiency: the optimal operation of systems of devices to save energy (aka intelligent efficiency) including providing other energy benefits such as demand response.

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1 Executive summary

The objective of this desk research study is to examine new battery technologies suited to powering small devices such as IoT, actuators and sensors, and portable devices such as mobile phones and laptops.

Topics to be covered include:

- Overview/exploring of emerging and existing energy storage technologies.
- Analyse the pros and cons of emerging and existing battery technologies, including the aspects of
  - Performance (storge capacity, power density, charging time, etc.)
  - Environmental impacts (very general analysis)
  - Cost
  - Market readiness

The battery technologies examined for this report are rechargeable batteries (secondary batteries) mainly intended for mobile devices that include mobile phones, smartphones, tablets, handheld gaming devices, laptops, power tools, smartwatches, smart speakers, IoT devices, e-scooters and e-bikes.

The demand for batteries is growing fast, and with the outlook to electrification of our transport sector, this demand is expected to increase by around a factor 10 in the next decade. Consumer electronics, including mobile devices, are expected to require a 60% growth in energy storage capacity over the next decade. For those reasons, new technologies must be invented and/or developed to supply the growing demand more efficiently than the current technologies.

As for existing technologies lithium-ion batteries (LiB) are one of the key enablers of the small sized portable devices we have today. With high power and energy density, low self-discharge rate and long lifetimes, LiB outcompeted the Ni-CD and Ni-MH re-chargeable alternatives for most use cases in the 2000s. LiB will likely remain the best alternative for the next few years. For this reason, LiBs are the existing battery technology that will be investigated in this report. Lead batteries, which are still available on the market especially as start batteries for ICE (Internal Combustion Engine) vehicles are considered an obsolete technology and not included in the scope.

There are however also many disadvantages for LiBs: The electrolyte solvent is flammable; the cathode often contains cobalt, which is entails some ethical problems due to the toxic environment and poor working conditions; and lithium is a not an abundant resource, with a limited production capacity that is currently not sufficient to cover the electrification targets.

The different types of LiBs differentiate mostly by the choice of cathode alloy they utilize, which changes the different performance characteristics, like energy density, power density, cycle time, price and voltage. The following typical LiB chemistries are detailed in the report: LCO (lithium cobalt oxide), LFP (lithium iron phosphate), NCA (lithium nickel cobalt aluminium oxide), NMC (lithium nickel cobalt), LMO (lithium manganese oxide spinel) and LTO (lithium titanate oxide).

The following emerging battery technologies are presented and assessed:

- Lithium metal anode
- Lithium Sulphur Batteries (Li-S)
- Solid State Lithium Batteries (SS-LiB)
- Sodium ion batteries (SiB)
- Lithium air batteries (LABs)
- Silicon anode
- Anode free batteries
- Zinc-air battery
- Aluminium-air battery
- Silver-zinc battery
- Carbon nanotubes
- Super capacitors

While a lot of existing and emerging battery technologies have potentials for various markets and products, the combination of their characteristics makes some more likely than others to take up significant market shares. Dominant future lithium-ion chemistries are expected to be NMC (lithium nickel cobalt, especially in their nickel-rich variant NMC-811), NCA (lithium nickel cobalt) and LFP (lithium iron phosphate). Other and newer emerging battery technologies may also enter the market, however, expected to still have a lower market penetration regarding volume in the coming 5-10 years.

Main areas impacting market opportunities are performance, lifetime, sustainability performance, costs and safety, however safety is not in scope of the current study. Hereinunder are lifetime aspects and development of repair, repurposing and recycling.

The conclusion is that the innovation in battery technology is moving at pace, both in terms of improving on existing technologies such as optimising lithium-Ion batteries, and in terms of developing new battery technologies from the bottom up, such as sodium batteries. While battery technology receives a lot of funding, it still takes a long time for a new or improved battery technology to reach the market (around 20 years). Therefore, despite a large effort from research facilities and private corporations, the lithium-ion technology still prevails in mobile devices and EVs, and some manufacturers even move towards existing technologies that were thought to be outdated, rather than bet on new technologies for the short term.

The recommendations are to:

- Make a policy effort to use better battery technologies than LCO in small portable devices due to their inferior quality in many aspects, though it is still the prevalent battery technology for these devices
- Ensure technology neutrality
- Ensure due diligence or other ethical sourcing principles are introduced for problematic resources
- Focus research funds on batteries with low or no use of critical raw materials (CRMs), and raw materials that are scalable
- Limit the environmental impact of battery production through LCA or carbon footprint requirements
- Focus on supporting recycling and other circular economy approaches (improved Battery Management Systems, recycling possibilities and technologies, design for recycling, re-purposing)

2 Introduction

The battery technologies examined for this report are rechargeable batteries (secondary batteries) mainly intended for mobile devices that include mobile phones, smartphones, tablets, handheld gaming devices, laptops, power tools, smartwatches, smart speakers, IoT devices, e-scooters and e-bikes. EVs are not as such in scope of EDNA, however, because the main battery market development is very much related to EVs (see Figure 1), throughout the report, we make references to EVs.

Common for all the mentioned products are that they are mobile and can operate for extended periods of time using a built-in battery. Battery technology is a key enabler for more mobile devices, and future advancements allow new types of products to be mobile. This is best exemplified by the increasing amount of different power tools, home appliances, computers and speakers that today are battery-driven. Even though battery-driven products often replace mains-powered products, battery-driven products also replace petrol-fuelled products such as for gardening tools. Both existing (i.e. commercialised) and emerging power storage technologies are included in this report, as well as information on energy harvesters based on the EDNA report on Energy harvesting technologies for IoT[1].

The current shift towards battery-driven products is expected to continue. The innovation space for batteries has grown rapidly, and more than seven times more battery-related patents are filed in 2020 compared to year 2000 and prices for energy storage has dropped by 90% over the last decade[2]. This development is expected to continue in the next decade, where prices are expected to further drop 66-80% compared to current prices. So, the development is fast, but the demand is likewise strongly expanding. IEA expects the market to increase 50 times by 2050 if the global green transition goals are to be met, which also is assumed to benefit mobile devices[2].

Topics to be covered in this report include:

- Exploration of emerging and existing energy storage for small devices.
- Analysis of the pros and cons of emerging and existing battery technologies, including the aspects of:
  - Performance (energy density, cycling life, charging and discharge rate etc.)
  - Sustainability performance (Carbon footprint, general analysis of resource consumption and constraints, especially with regards to rare earth materials and critical raw materials, recycling)
  - Cost
  - Maturity for commercialization

The demand for batteries is growing fast, and with the outlook to electrification of our transport sector, this demand is expected to increase by around a factor 10 in the next decade, as depicted in Figure 1. Consumer electronics, including mobile devices, are expected to require a 60% growth in energy storage capacity over the next decade. For those reasons, new technologies must be invented and/or developed to supply the growing demand more efficiently than the current technologies. The cylindrical cells and chemistries used in EV battery packs is also used in power tools, e-mobility devices, battery garden tools, battery vacuum cleaners, power banks, while smaller products like notebooks, smartphones, e-readers and alike use pouch cells with high cobalt LCO chemistry, not used in the EV market. Therefore, less positive spill-over effects from the huge R&D efforts in the blooming EV battery sector, is expected in smaller portable devices, given that they continue researching within the same chemistries.

[1] IEA 4E EDNA, 2018, Energy Harvesting Technologies for IoT Edge Devices
[2] IEA Innovation in batteries and electricity storage, A global analysis based on patent data (2020)

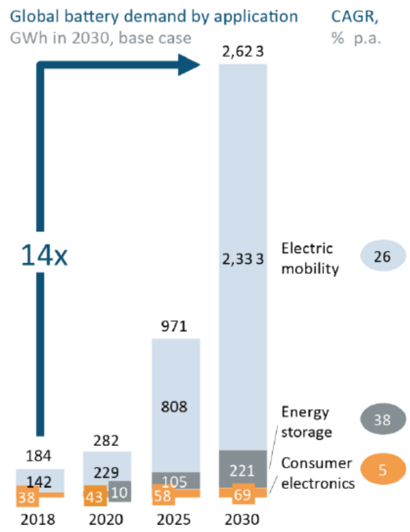

Figure 1: Battery demand growth globally towards 2030[3]

3 Existing and Emerging Battery Technologies

3.1 Scope and definition

This chapter aims to provide an overview of emerging and existing battery technologies typically used for mobile devices. While there are approaches to store energy for use in a wide range of applications as shown in Figure 2, the main goals and requirements for small mobile devices are modularity, flexibility, and compactness (in terms of both weight and volume), of which the latter is likely the most critical. Therefore, many of the same types of batteries are used across different types of mobile devices, even though the products may be quite different.

The electrochemical battery technology is the most compact energy storage method[4] compared to other energy storage technologies such as chemical, electromechanical and thermal (see these technologies in Figure 2). Electrochemical technology is also the only energy storage technology used in mobile devices, which is why we only focus on this technology for batteries and electrostatic supercapacitors for future perspectives.

A standard battery consists of 2 electrodes; a negatively charged anode, and a positively charged cathode. An electrolyte enables ionic transfer between the two electrodes through the separator, which insulates the two sides electrically. Thereby the battery can be charged by applying an external electric current between the anode and cathode, which in case it was a lithium-ion battery would move Li+ ions internally to the anode, while drawing electrical current from the battery will reverse the ionic movement[5].

Lithium-ion batteries the far most electrochemical battery technology used today and most of the promising emerging battery technologies are also lithium based.

There are a few other alternative prospective battery chemistry and technologies that we will briefly describe: Carbon nanotubes, super capacitors, zinc-air and silver-zinc.

As seen in Figure 2, battery cells can be categorised based on shape, electrolyte phase and chemistry. Generally, three different cell shapes are distinguished: cylindrical, pouch, and prismatic, though specific for smaller portable devices the category of coin and pin batteries exist as well. Cylindrical cells are the most commonly used type, and are widespread in e.g., power tools, laptops, and for personal mobility. In new slim laptops, lithium-polymer cells with gel-based electrolyte and no casing are used in the pouch shape like in many smartphones. In smartwatches, other wearables and IoT devices, you will find small pouch and coin or pin batteries.

[3] European Commission, 2020, Batteries Europe: Strategic Research Agenda for batteries
[4] Deloitte, 2015, Energy storage: Tracking the technologies that will transform the power sector ,19.
[5] DTU Energy, 2019, Whitepaper: Energy storage technologies in a Danish and international perspective, 33.

Typical applications for mobile devices include[6]:

- IoT, MEMS (Micro Electro-Mechanical Systems), medical implantable (about 1 mAh)
- Smart cards, skin patch, RFID (about 10 mAh)
- Wearables, E-textile, medical device (about 100 mAh)
- Smartphone, tablet, power tool, toy (about 1 Ah)
- E-scooters and e-bikes (about 10 Ah)

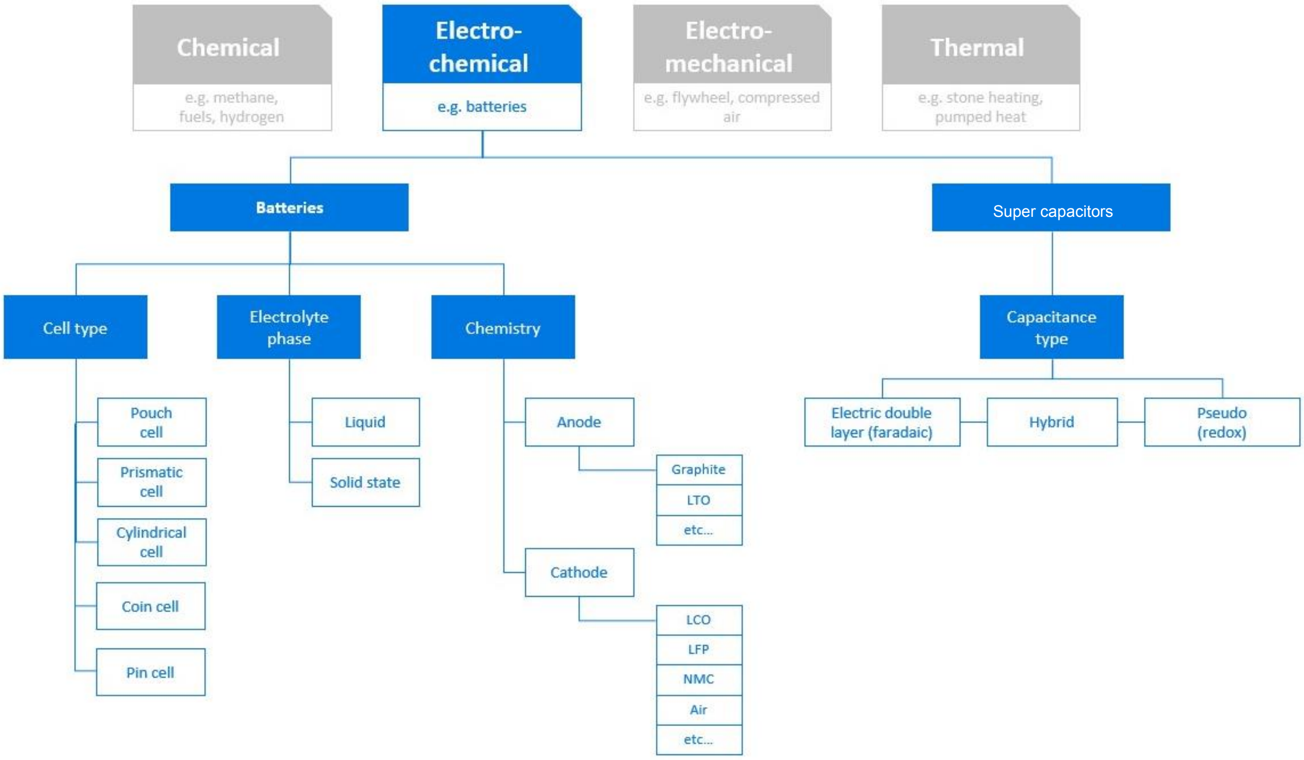

Figure 2: Overview of battery technologies. Electro-chemical technologies are in scope of this study.

The technologies and the future of electrochemical batteries depend on a handful of parameters such as chemical composition combined in multiple ways – making many different specific battery technologies – both present and future. In this report, main combinations and most likely mix of these parameters will be investigated.

3.2 Existing technologies

Lithium-ion batteries (LiB) are one of the key enablers of the small sized portable devices we have today[7]. With high power and energy density, low self-discharge rate and long lifetimes, LiB outcompeted the Ni-CD and Ni-MH re-chargeable alternatives for most use cases in the 2000s. LiB will likely remain the best alternative for the next few years. For this reason, LiBs are the existing battery technology that will be investigated in this report. Lead batteries, which are still available on the market especially as starter batteries for ICE (Internal Combustion Engine) vehicles are considered an obsolete technology and not included in the scope.

There are however also many disadvantages for LiBs.

[6] IDTechEx, idtechex.com/de/research-report/flexible-printed-and-thin-film-batteries-2016-2026-technologies-markets-players/463

[7] Liang et al, 2019, a review of rechargeable batteries for portable electronic devices, Energy Environ. Sci.,2021, 14, 4712

LiBs consist of a graphitic anode, a lithium-based cathode (including other elements as well to enhance performance) and a liquid electrolyte based on lithium salt. Copper and aluminium are the most common metals used as current collectors at anode and cathode, respectively. The electrolyte solvent is flammable, which is a challenge in many applications, such as explosion risks in smartphone batteries or fire hazard of electric vehicles. The cathode often contains cobalt, which is entails some ethical problems due to the toxic environment and poor conditions that cobalt miners are working under mainly small-scale mines in DR Congo. Lastly, lithium is a limited resource whose production capacity is currently insufficient, which is a challenge in the supply chain and long-term future of the technology, though a higher circularity of LiB would alleviate the resource scarcity.

LiB development has accelerated over the years and the technology has continuously improved, but scientists fear that the lithium technology is reaching its maximum theoretical energy density and new technologies must be invented to enable long distance driving in EVs[7]. Some of the most promising future technologies, which will be expanded upon in Section 3.3, show potential to offer higher energy density, safety, lower cost and batteries from abundant materials.

3.2.1 Types of lithium-ion batteries (LiB)

The different types of LiBs differentiate mostly by the choice of cathode alloy they utilize, which changes the different performance characteristics, like energy density, power density, cycle time[8], price and voltage. In Table 1, performance data for typical LiB chemistries are presented, along with the mobile device applications they are used in.

[8] Normally listed as how many charge/discharge cycles the battery can survive before decreasing its energy storage capacity to 80%.

Technology	Anode	Cathode	Use case	Gravimetric energy density [Wh kg^{-1}]	Volumetric energy density [Wh L^{-1}]	Battery pack cost [USD kWh^{-1}]	Volume weighted average pack cost [USD kWh^{-1}]
LCO Lithium cobalt oxide	$LiCoO_2$	Graphite	Mobile phones, laptops, tablets, cameras	160-210[10]	340-580[10]	250-450[9]	n/a
LFP Lithium iron phosphate	$LiFePO_4$	Graphite	Power tools, e-bikes	80[10]-200[11]	120-300[10]	85*-99-225[12]	108[12]
NCA Lithium nickel cobalt aluminium oxide	$LiNiCoAlO_2$	Graphite	Medical devices, laptops	150-300[10]	680-760[10]	115-415[12]	120[12]
NMC Lithium nickel-manganese- cobalt	$LiNiMnCoO_2$	Graphite	E-bikes, portable devices, industrial, electric vehicles	150–220[10]	580-750[10]	115-525[12]	167[12]
LMO Lithium manganese oxide spinel	$LiMn_2O_4$	Graphite	E-bikes, portable devices	100[10]-150[13]	220-400[10]	n/a	n/a
LTO Lithium titanate oxide	$LiNiMnCoO_2$ or $LiMn_2O_4$ b.u.	$Li_4Ti_5O_{12}$	Good for opportunity charging	50-80[14]	n/a	600-770[15]	n/a

*Table 1: Comparison of different LiB technologies. *If CATLs new compact LFP blade design is used.*

The data provided is assembled from many different sources, and some are more recent than others, e.g., LFP volumetric and gravimetric energy density comes from two different sources from different years, which means they are almost but not 100% compatible.

LCO is an early generation LiB, which took over the market for smaller portable devices in the early 2000s (from NiMH), due to it having the highest energy density amongst LiBs when it was put on market. It is still the preferred

[9] www.arpa-e.energy.gov/sites/default/files/documents/files/Jaffe_RANGE_Kickoff_2014.pdf
[10] Durmus et al., Adv. Energy Mater. 2020, 10, DOI: 10.1002/aenm.202000089
[11] www.pv-magazine.com/2021/07/29/catl-claims-to-have-made-sodium-ion-batteries-a-commercial-reality/
[12] www.bloomberg.com/news/newsletters/2021-09-07/production-delays-lead-some-automakers-to-try-a-low-cost-low-range-battery
[13] www.large.net/news/8fu43my.html
[14] https://batteryuniversity.com/article/bu-205-types-of-lithium-ion
[15] https://solartechadvisor.com/lithium-titanate-batteries/

chemistry amongst small portable devices, even though other LiB technologies like NMC and NCA has surpassed its performance. It is hard to find information about why this LCO technology lock-in has happened for small portable devices, holding an inferior standard, from the alternatives available also regarding rare earth metal content. LCO battery cathodes contain the highest amount of cobalt (~ 60 % cobalt[16]) compared to other cobalt containing LiBs where NMC has up to 15%[17] and NCA ~9%. The cobalt content is also reflected in the price difference amongst the 3, with LCO having highest price per kWh battery. Furthermore, ageing is a downside for LCO[18], which makes it a bad choice for EVs, e-mopeds and smaller EV vehicles (because they have a longer lifetime than small portable devices). LCO, NMC and NCA is the highest ranking amongst LiBs regarding energy density and is therefore used in products needing lightweight and compact batteries. Though they all have lower thermal runaway temperature[19], making them the most risky LiB batteries regarding fire and explosion danger[20].

The improvement of NMC technology has been linked to the nickel content in each cathode generation. The numbers after NMC represent the molar compositions, e.g. NMC111 would be LiNi1/3Mn1/3Co1/3O2. The difference in composition in kg/kWh is shown in Figure 3.[21]

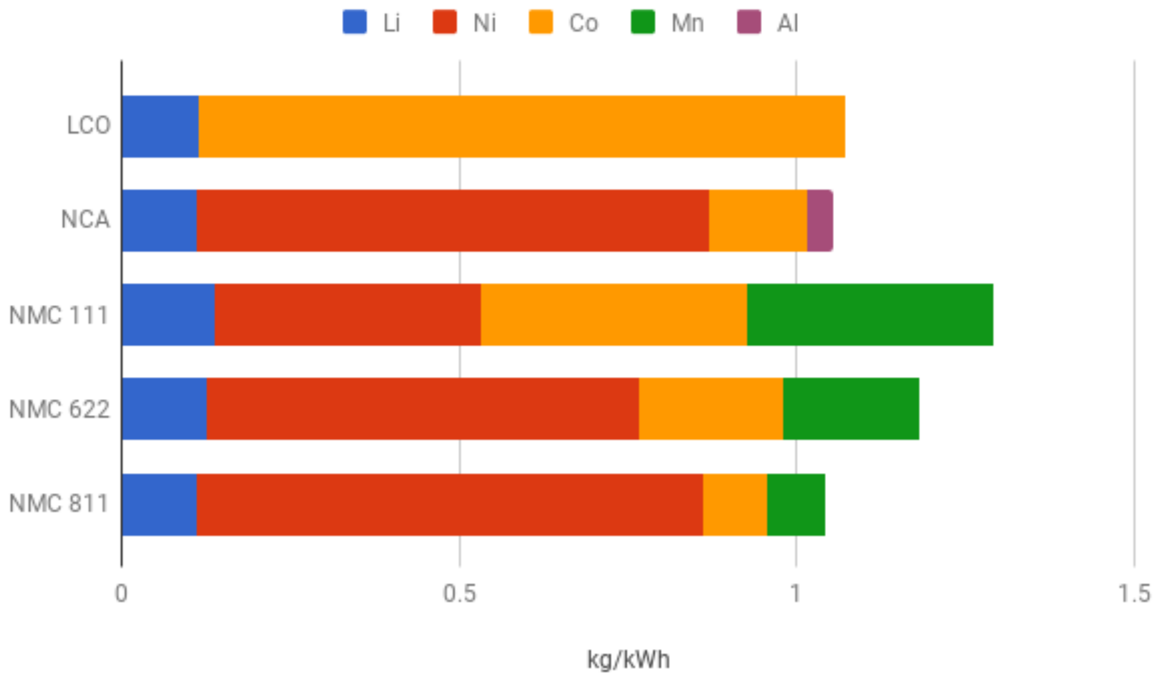

Figure 3: Comparison of different battery chemistries – LCO, NCA, and NMC – and their material/elemental composition

LFP is one of the safest and long-lived cathode materials, partly due to its low voltage, which however results in a lower energy density. LFP batteries is free from cobalt and nickel and utilises low price high abundance iron instead, resulting in a lower price per kWh. The recent trend in the lower range EV market is to move from NMC cells to LFP, e.g., Tesla and VW are now partly producing their low range vehicles with LFP battery packs[22] [23]. Due to LFPs high melting point there is reduced potential for thermal runaway. Furthermore, new battery cell type design like the blade from CATL has enabled LFP batteries to withstand damage and be penetrated with low risk of explosions and fire,

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[16] https://www.cruxinvestor.com/articles/the-ultimate-guide-to-the-cobalt-market-2021-2030f
[17] But newer NMC chemistries like NMC622 or NMC811 has much less.
[18] The energy a LCO battery can deliver per cycle fades over time, even though it is not cycled, resulting in lower usable lifetime than NMC and NCA.
[19] Thermal runaway is caused by high temperatures, triggering a chain of exothermic reactions, leading to uncontrollable rise in temperature, causing fire and explosion danger.
[20] Batteries in the Nordics, change for circularity.
[21] https://researchinterfaces.com/know-next-generation-nmc-811-cathode/, Fu et al., Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals (DOI: 10.1016/j.joule.2017.08.019)
[22] https://www.cnbc.com/2021/10/20/tesla-switching-to-lfp-batteries-in-all-standard-range-cars.html
[23] https://oilandgas-investments.com/2021/investing/lfp-batteries-are-winning-the-ev-race-but-wheres-the-ex-china-supply/

compared to the usual high energy density cells[20]. Recent advances in energy density has put LFP close to LCO levels, possibly enabling them to take on market shares also in the compact battery market.

LMO has a low energy density, and low cycling life (300-700 cycles) but has a high discharge rate 1-10 C, making it a good choice for power tools.

LTO has a lithium titanite oxide anode, in contrary to graphite used by other LiBs, and therefore has a much lower voltage (2.6 V compared to 3.6 V for most other LiBs). This gives it the lowest energy density amongst LiBs (see Table 1), but superior charge and discharge speeds, and cycling life of 20000. Therefore, it has been used in busses where opportunity charging is possible[24]. The anode material is expensive and LTO is therefore the most expensive LiB.

3.3 Emerging Battery Technologies

Currently, a lot of effort and research is going into looking for new chemistries for batteries. Energy density is anticipated to increase, mainly to improve the range of EVs. Also, costs must decrease to meet the future demand for batteries to support electrification and green transition of global economies. The energy density of batteries is determined by their specific capacity (the total amount of electricity generated from electrochemical reactions in the battery, expressed in *ampere hours*) and nominal voltage (e.g., LiB NMC voltage is 3.7 volts) as seen in Equation 1, research has to a large extent been focused on increasing these two parameters.

$$Energy\ density\ (\frac{Wh}{Kg}) = \frac{specific\ capacity\ (ampere\ hours)\ X\ operational\ voltage\ (Volts)}{Mass\ of\ battery\ or\ battery\ pack\ (Kg)}$$

Equation 1: Energy density's relation to specific capacity, operational voltage and mass of battery.

But high energy density is useless if the battery has a short lifetime, therefore another essential research focus has been high cycling time performance.

The trends are leaning towards using more nickel (and less cobalt) in the cathode of the batteries[25] and introducing silicon to the graphite anode; towards higher energy density; solid-state batteries and lithium metal and silicon as anode. It is also likely that the market for already-developed chemistries like LFP and manganese batteries will become more important. The re-introduction of these chemistries is a current trend in the automotive sector. The reason why consumers and companies find the lower range acceptable for automotive applications is that the vehicles can be made cheaper and safer at the same time. The question is if portable devices, or sub sectors thereof can and will follow the trend. For the smaller portable devices, a shift to LFP, would come with compromises, either lowering the runtime of the battery, or increasing the volume. Though future anode materials could change this. In the following section emerging battery technologies are presented.

3.3.1 Lithium metal anode

Lithium metal anode is for many battery researchers seen as the holy grail to high gravimetric and volumetric energy density. This type of anode exists in both a LiB constellation with liquid electrolyte and an NMC or NCA cathode showing future promise of reaching 400 Wh/kg, and in a solid electrolyte constellation (see Solid State Lithium Batteries below) reaching 500 Wh/kg. Though the drawback with these constellations from a resource perspective is that both anode and cathode contain lithium, which hopefully will be outweighed by the increased energy density.

In 2021, Sion Power announced their lithium metal anode battery cell at 400 Wh/kg and 810 Wh/L at 700-800 cycling to 80% State Of Health (SOH)[26], while their lower cycling (200), even higher energy density batteries was announced in 2019.

[24] Short time between charging opportunities.
[25] The EU research initiative Battery 2030+
[26] SOH is an indicator how much of the batteries initial energy capacity is left.

3.3.2 Lithium Sulphur Batteries (Li-S)

Li-S batteries consist of a sulphur cathode and a lithium metal anode and has a five times higher theoretical energy potential than LiB. The availability of sulphur is plentiful, sustainable, and very inexpensive, making it one of the most favourable future technologies for delivering low-cost and high efficiency of batteries.

There has been an extensive research focus on Li-S from academia publishing 3461 papers the last 10 years[27], where the prevailing subject has been the sulphur cathode, partly due to the 80 percent volume expansion at charge, which causes electrode collapse. This is also one of the prevailing reasons why the technology is still not practically developed in big scale.

3.3.3 Solid State Lithium Batteries (SS-LiB)

SS-LiB are promising as they are based on the LiB technology but replaces the flammable liquid electrolytes with solid electrolytes. This not only eliminates the fire hazard but also increases energy potential of these batteries. There is still some way to go for the technology to be an important competitor to other battery technologies. However, the company Gogoro has just announced what they call the world's first-ever solid state swappable electric vehicle battery[28]. Bolloré states that they are the *only company in the world that markets and controls every step of the design and manufacturing of an "entirely solid" battery*[29]. Another source expects market growth rates of 35% CAGR 2021-2027[30]. However, the development necessitates large capital expenditures for research, development and the establishment of production facilities. Production price is still much higher compared to traditional LiBs. The market growth may take place primarily for single-cell batteries for IoT devices, wearables etc.

3.3.4 Sodium ion batteries (SiB)

New types of metal-ion batteries that are not lithium-ion based may become important, for example sodium batteries. According to the Swedish company Altris, they have similar performance as LFP, but ageing is not yet fully known[31]. Future applications of sodium batteries may be cheaper cars where LFP is currently used, e-bikes/scooters, power-tools, stationary storage, buses, and construction equipment[32]. Interesting is that CATL (Contemporary Amperex Technology Co., Limited; lithium-ion battery developer and manufacturer) has recently launched their first sodium-ion battery, reaching a medium energy density at 160 Wh/kg resembling LFP, while showing better low temperature performance, though no information on cycle life has been published[33].

Sodium is a promising material for battery production due to the abundant availability and low cost. Also, the similarity between lithium and sodium[34] makes the technology develop fast. However, sodium batteries have low energy density, so while they have high potential for stationary energy storage, they are likely not the future battery type for smaller portable devices, as they lack the compactness. They could potentially overtake market shares where LFP batteries are used, e.g., stationary storage systems and some e-mobility applications

3.3.5 Lithium air batteries (LABs)

LABs are a promising technology showing potentials alike SS-LiB. $Li-O_2$ consists of a lithium metal anode, a porous carbon cathode material, which allows the liquid electrolyte to be exposed to air, at which point O_2 and Li+ interacts. This concept shows huge energy density potential, as it neglects the weight of the cathode (except from the dissolved O_2). Though an open battery cell structure, allowing access to air, comes with deficits. One being safety issues due to possible electrolyte spillage or vaporization, while exposure of the reactive Li metal anode to air can be catastrophic. Research in polymer electrolyte, and coatings of the Li anode is some of the focus areas for the research community, trying to unlock the high theoretical energy potential[27].

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[27] Jianmin Ma *et al* 2021 *J. Phys. D: Appl. Phys.* 54 183001
[28] https://electrek.co/2022/03/08/gogoro-unveils-the-worlds-first-ever-solid-state-swappable-electric-vehicle-battery/
[29] https://www.bollore.com/en/activites-et-participations-2/stockage-delectricite-et-systemes/blue-solutions-films-plastiques/
[30] https://www.globenewswire.com/news-release/2022/04/04/2415345/0/en/Global-Solid-State-Battery-Market-Size-Share-Industry-Trends-Analysis-Report-By-Type-By-Capacity-By-Battery-Type-By-Application-By-Regional-Outlook-and-Forecast-2021-2027.html
[31] Altris, 2021. Personal communication with CEO Adam Dahlquist in Q2 2021
[32] https://battery2030.eu/research/roadmap/ Q2 2010
[33] https://www.greencarcongress.com/2021/07/20210730-catl.html Q3 2021
[34] Both alkali metals, i.e., periodic table first group elements.

3.3.6 Silicon anode

For many years scientists have looked to silicon as anode material which has a 10x higher energy potential than the default graphite anode found in lithium batteries. However, due to its 300% expansion when cycling, and degradation caused by silicon/liquid electrolyte interaction, it is very problematic to create a silicon anode capable of surviving a reasonable amount of charge/discharge cycles. Amprius started distributing its batteries with different LiB cathodes and their 100% silicon anode on a nanowire current collector in 2021. One battery type they made for low charge / discharge levels (1/5 C) reached 365-430 Wh/kg and 875-1240 Wh/L, while at normal charge/discharge levels (1 C) it reached 325-360 Wh/kg and 780-870 Wh/L[35]. Both lasted 150-300 cycles before losing 80% capacity. Showing the potential to half the volume of a LCO pouch cell, for a laptop or cellphone if higher cycling is reached. Amprius has stated that the production will be scaled up for bigger markets in 2023, while also working on EV market battery with higher cycling capabilities.

Another approach to unlock the potential of silicon anodes, is a combination of a silicon anode, NMC cathode and a solid sulphide electrolyte is showing promising results of 500 charge/discharge cycles[36]. The lab tests had similar volumetric energy density than LiBs but showed future promise to reach over 900 Wh/L[37]. Some manufacturers already incorporate small percentages of Silicon into Li-ion anodes (5-10%). The main limitation is that silicon expands in charging scenarios, though the anode is a porous structure that mitigates the volume expansion of silicon[38].

3.3.7 Anode free batteries

Anode free batteries has recently drawn attention, as the cell architecture show high energy density potential. An anode free battery has no metal deposited on the anode current collector before first charge, but when charged Li+ from the cathode will move to the current collector. The technology is in its infancy, but has potential for low price, high specific energy, with lab tests of lithium pouch cells reaching 200 cycles before reaching 80% energy capacity[39]. The anode free configuration is also seen lab tested for sodium metal batteries[40].

3.3.8 Zinc-air battery

Zinc-air batteries based on existing battery technology are not rechargeable. They are powered by oxidizing zinc with oxygen from the air and have high energy densities and are relatively inexpensive to produce. They are mainly used as small button cell primary batteries for hearing aids, cameras, watches, etc. and as larger batteries for railway signals, safety lamps etc.

However, rechargeable zinc-air batteries based on emerging battery technology using new materials[41] are coming to the market. They may reach high energy density (1353 Wh/kg excluding oxygen); low production costs (currently <100 USD/kWh, and potentially < 10 USD/kWh1) and better safety[42].

3.3.9 Silver-zinc battery

Silver-zinc rechargeable batteries are used for special applications e.g. in non-typical form factors as flexible batteries and as button cells. It is now being developed for more general-purpose batteries such as for laptops, IoT, wearables, industrial etc., which may have longer runtime compared to LiB. However, they still have short lifetimes.[43] The battery technology is not really an emerging technology, but has been included due to broader usage cases in recent years.

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[35] https://www1.grc.nasa.gov/wp-content/uploads/5.-Amprius.pdf
[36] A New Solid-state Battery Surprises the Researchers Who Created It, https://ucsdnews.ucsd.edu/pressrelease/meng_science_2021, visited 20/02/2022
[37] Tan et al., 23 September, 2021, Vol 373, Issue 6562 • pp. 1494-1499, DOI: 10.1126/science.abg7217, Carbon-free high-loading silicon anodes enabled by sulfide solid electrolytes, p.1498
[38] https://www.autoweek.com/news/industry-news/a38280205/nanograf-silicon-anode-battery-technology/
[39] A. J. Louli et al 2021 J. Electrochem. Soc. 168 020515 Optimizing Cycling Conditions for Anode-Free Lithium Metal Cells
[40] https://sites.utexas.edu/gain/anode-free-sodium-metal-batteries/
[41] Science, A rechargeable zinc-air battery based on zinc peroxide chemistry, 1 January 2021, https://www.science.org/doi/full/10.1126/science.abb9554
[42] CIC energiGUNE blog post. https://cicenergigune.com/en/blog/rechargeable-zinc-air-batteries
[43] Battery University, https://batteryuniversity.com/article/bu-217-summary-table-of-alternate-batteries

3.3.10 Carbon nanotubes

Carbon nanotubes can be described as a 2-dimensional graphene layer rolled to a tube, showing high strength and high conductivity capabilities. It is used to strengthen electrodes and maximise their conductivity, increasing the amount of charge/discharge cycles it can survive e.g. by keeping volume expanding and cracking electrodes conductive[44] while at the same time reinforcing them.

Aligning CNTs vertically (VACNT) like trees in a forest, offers promising potential to a variety of applications in both batteries and supercapacitors. In the context of batteries, application as a base for anodes VACNT offers a uniform mesh through which electrolyte more easily can flow and have access to a larger surface area per weight unit than the usual anode material[45]. Furthermore, the structure allows for faster battery charge and discharge. Different anode materials (e.g., silicon and lithium) can then be deposited into the VACNT structure. A structure which can absorb eg., lithium and silicon's 80 and 300 percent volume expansion respectively, and thereby opening possibilities for long-lasting high-capacity anode materials, with high cycling count.

Finding a cost-effective method to grow VACNT has kept the technology away from integration in mass markets, but recently NAWA Technologies announced mass production to begin in 2022[46], and their supercapacitor factory opening mass production in 2023[47].

NAWA claims that introducing their VACNT electrode in a given battery would increase its power density ten times, while increasing lifetime up to 5 times. Their development partner battery manufacturer SAFT shows that LiBs using their electrode technology at a minimum would double the energy density[48].

3.3.11 Magnetically aligned graphite electrodes

Aligned graphite technology is used to improve charging speed. The electrochemical performance of a battery containing a thick (about 200 μm), highly loaded (about 10 mg cm−2) graphite electrode can be enhanced by fabricating anodes with an out-of-plane aligned architecture using a low external magnetic field. This magnetic alignment approach leads to a specific charge up to three times higher than that of non-architectured electrodes at a rate of 1C49.Battrion and Jagenberg Group have partnered for deploying anode pilot lines and full electrode production lines with this technology to produce negative electrodes with ultra-low resistance for fast-charging applications.[50]

3.3.12 Lithium-ion capacitors

A lithium-ion capacitor (LIC) is a hybrid type of capacitor classified as a type of supercapacitor (see next section). The anode is the same as those used in lithium-ion batteries and the cathode is the same as those used in supercapacitors. The anode of the LIC consists of activated carbon material, often pre-doped with lithium ions. This pre-doping process lowers the potential of the anode and allows a relatively high output voltage compared to other supercapacitors, which could be more useful for power tools.

3.3.13 Super capacitors

Super capacitors are electrochemical energy storage devices like batteries, but they store the electrical charge directly on the surface of a material, while batteries store it with chemical reactions[51]. This allows supercapacitors to be charged and discharged with no degradation, as opposed to batteries[52]. Super capacitors are often combined with batteries in EV powertrains, where they are utilized for fast acceleration and brake energy regeneration, as they have extreme charge/discharge rates and a higher power density than batteries as seen in Figure 4 below.

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[44] If an electrode cracked into two pieces, the CNT would keep the electrical connection between the two parts, while also reinforcing the electrode, so cracking in the first place would be diminished.
[45] Nassoy, F. et al.(2019). Single-Step Synthesis of Vertically Aligned Carbon Nanotube Forest on Aluminium Foils. *Nanomaterials (Basel, Switzerland)*, *9*(11), 1590. https://doi.org/10.3390/nano9111590
[46] https://chargedevs.com/newswire/nawa-technologies-begins-production-of-vertically-aligned-carbon-nanotube-material/
[47] https://tech.eu/2022/01/20/how-nawa-is-pushing-clean-and-efficient-energy-storage-boundaries-with-e18-3-million-funding
[48] www.sae.org/news/2021/03/nawa-aims-for-5-minute-ev-charge
[49] Billaud, J., Bouville, F., Magrini, T. et al. Magnetically aligned graphite electrodes for high-rate performance Li-ion batteries. Nat Energy 1, 16097 (2016). https://doi.org/10.1038/nenergy.2016.97
[50] https://battrion.com/
[51] U.S. Department of Energy, 2020, Energy Storage Grand Challenge Roadmap, p. 98-99
[52] DTU Energy, 2019, Whitepaper: Energy storage technologies in a Danish and international perspective, 138-139.

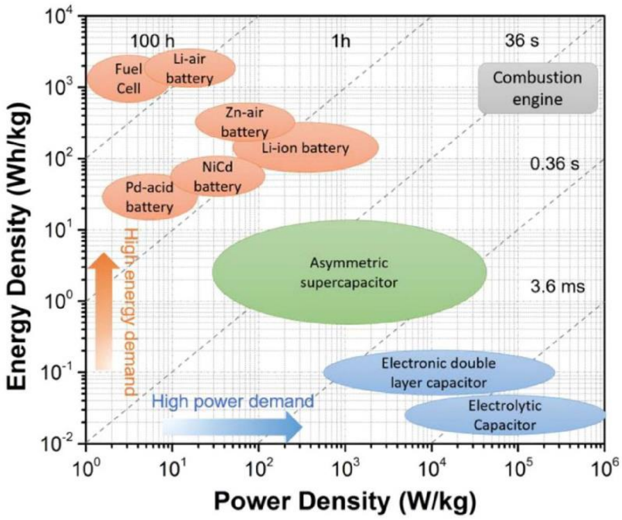

Figure 4: The ragone plot depicts performance of different electrical energy-storage technologies, with respect to power and energy density. Furthermore, discharge times is shown[27].

A supercapacitor has two electrodes normally from activated carbon (see electric double layer in previous Figure 2), a separator and an electrolyte, storing energy at the surface of the electrodes electrostatically, without moving ions between the electrodes like batteries. The pseudo capacitance supercapacitors use ionic movement as batteries to enhance the energy storage capacity, while slowing down charge and discharge speed. In general, supercapacitors have much higher power density (i.e. being able to provide more power (watts) per weight unit), but lower energy density (i.e. being able to provide less energy (watt-hours) per weight unit) [53] than lithium-ion batteries.

Supercapacitors are also used in recent tram systems for public transport[54] and other systems which need high power, and often can be recharged. The technology's caveats are its one order of magnitude lower energy density factor, high price, and a high self-discharge, making it an unexpected choice for most of the products in the scope of this report. Though with price and volume improvements, they might be useful in niche market for products where high power and sub 30 seconds charging is beneficial, even though the time between charges would be up to 10 shorter if the weight of the product should be kept at the same level. An example could be the use case of a power tool which normally would come with 2 batteries for professional use cases, because of the long charging time. With a supercapacitor as energy-unit, charge time would be sub 30 seconds and therefore only one energy unit would be needed. Regarding recyclability it has been observed that lithium supercapacitors can be created from the used graphite anode of LIBs[55].

3.3.14 Predicted shares of technologies

While a lot of existing and emerging battery technologies have potentials for various markets and products, the combination of their characteristics makes some more likely than others to take up significant market shares. Figure 5 shows the current and projected market shares of various lithium technologies for the EU as an example, both existing and developing, based on data from Circular Energy Storage[56]. This forecast also includes battery capacity expected for electric vehicles and energy grid storage. The forecast of the total projected capacity was compared to nine similar forecasts, concluding that five of the nine forecasts were lower and four higher. Beyond the technologies included in Figure 4, silicon-based anodes, solid or gel-based electrolytes, and new cell formats[57] will be introduced at scale and probably new battery types will be marginal and used for niche applications during this period.

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[53] www.thomasnet.com/articles/automation-electronics/super-capacitors/
[54] https://cmte.ieee.org/futuredirections/2016/11/02/supercapacitor-tram/
[55] (Divya, Natarajan, Lee, & Aravindan, 2020)
[56] Circular Energy Storage (2020) https://www.circularenergystorage-online.com/copy-of-placed-on-market-3 (paid subscription) Retrieved from the Internet and re-calculated in Q3 2021.
[57] E.g., bigger cylindrical cells are coming from Tesla, to decrease manufacturing time per kWh battery, and thereby price.

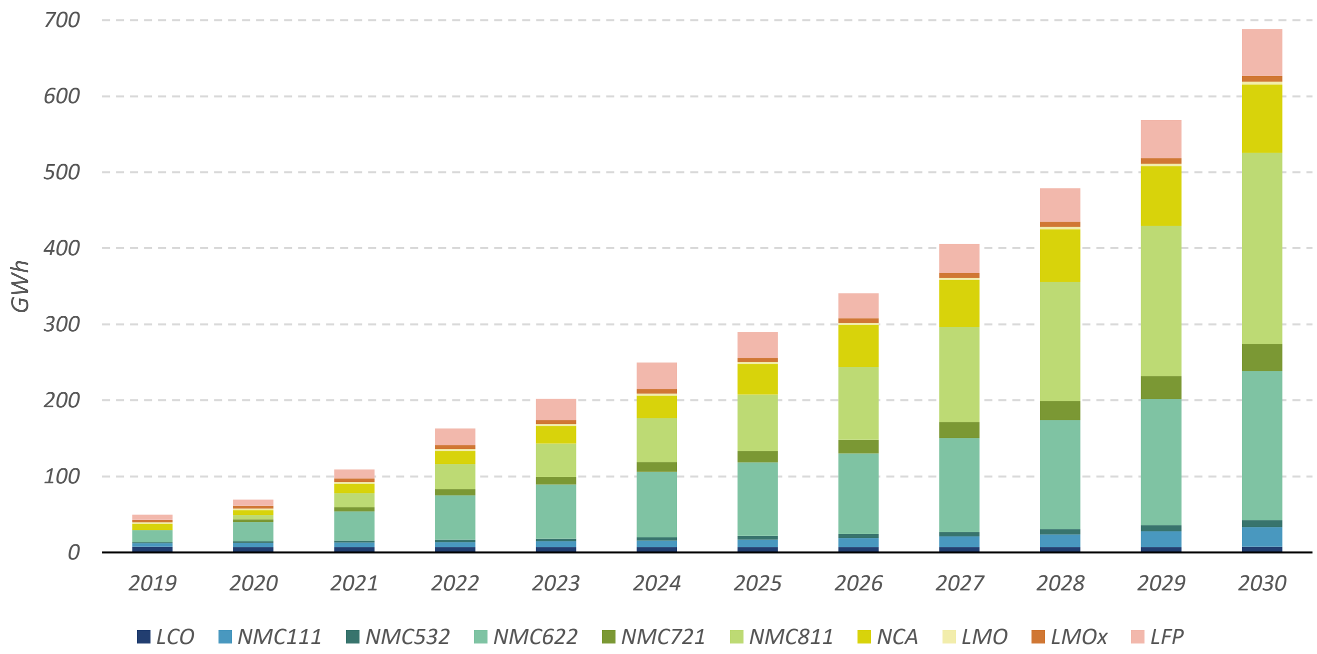


Figure 5: Current and future lithium-ion chemistry volumes placed on market in Europe measured in GWh[58]

[58] Circular Energy Storage (2020) https://www.circularenergystorage-online.com/copy-of-placed-on-market-3 (paid subscription) Retrieved from the Internet and re-calculated in Q3 2021.

4 Pros and cons of existing and emerging battery technology

The aim of the subtask is to provide an analysis of the pros and cons of emerging and existing battery technologies described in the previous subtask focussing on:

- Performance (energy density, cycling, charge and discharge rate).
- Lifetime of batteries: General analysis of different parameters like temperature, depth of discharge, level of charge, speed of charge and speed of discharge and their impact on a battery lifetime.
- Sustainability performance (general analysis): Focus will be on most relevant aspects such as CRM (Critical Raw Materials) and recycling.
- Cost: As far as possible, we will provide generic cost data for main groups of the base-cases, e.g. traditional size for mobile devices such as laptops and smartphones and for newer types of IoT devices. For most emerging technologies, cost forecasting studies will be presented.
- Maturity for commercialization: This will basically report if the storage technology is already applied in marketed devices or how far in development it has reached. IEAs technology readiness level (TRL) scoring system is used[59].

Battery technology is a topic with high focus, but a lot of the available information is focused on batteries for electric cars. Even though a lot of the information is based on cars, it is possible to draw conclusions to mobile devices regarding environmental performance impacts, including the content of critical raw materials, Global Warming Potential (GWP), etc.

4.1 Performance

In Figure 6 the different battery technologies and their potential gravimetric and volumetric energy densities are presented. Regarding the small portable devices (e.g., smartphones, tablets, wearables) high volumetric energy density (and to a lower degree gravimetric as well) is a key enabler for new products. Therefore, technologies further right than LiBs in Figure 6, is favourable to this product group. The most promising in that regard is lithium oxygen and solid-state batteries with lithium metal anode, while the later promise much better safety performance, which is also key to the small portable devices.

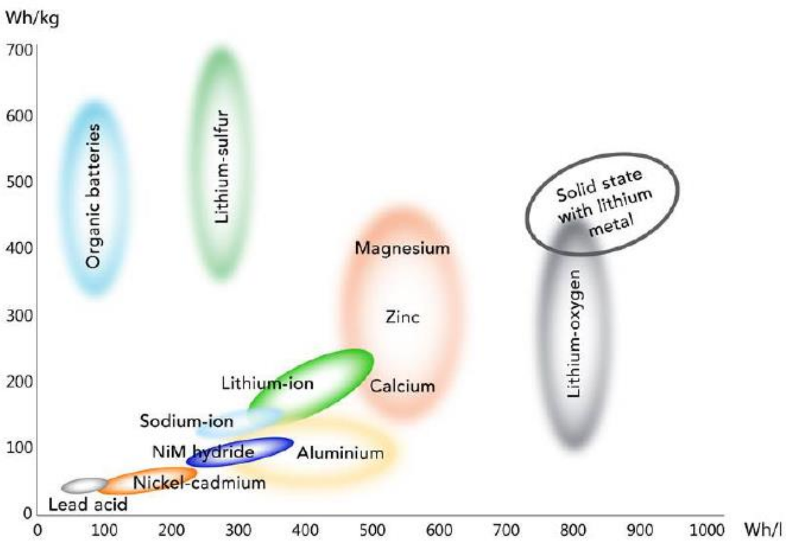


Figure 6: Battery performance of the different available and emerging technologies[60].

[59] https://iea.blob.core.windows.net/assets/355d9b26-b38c-476c-b9fa-0afa34742800/iea_technology-guide-poster.pdf
[60] Battery 2030+ Roadmap, Inventing the sustainable batteries of the future.

For power tools compactness is not as important as for small portable devices, regarding energy density, but more important is the discharge and charge time, which when taking weight into account for the first also can be expressed as power density (Watt/kg). In Table 2 discharge and charge time expressed in C-rate[61] can be observed.

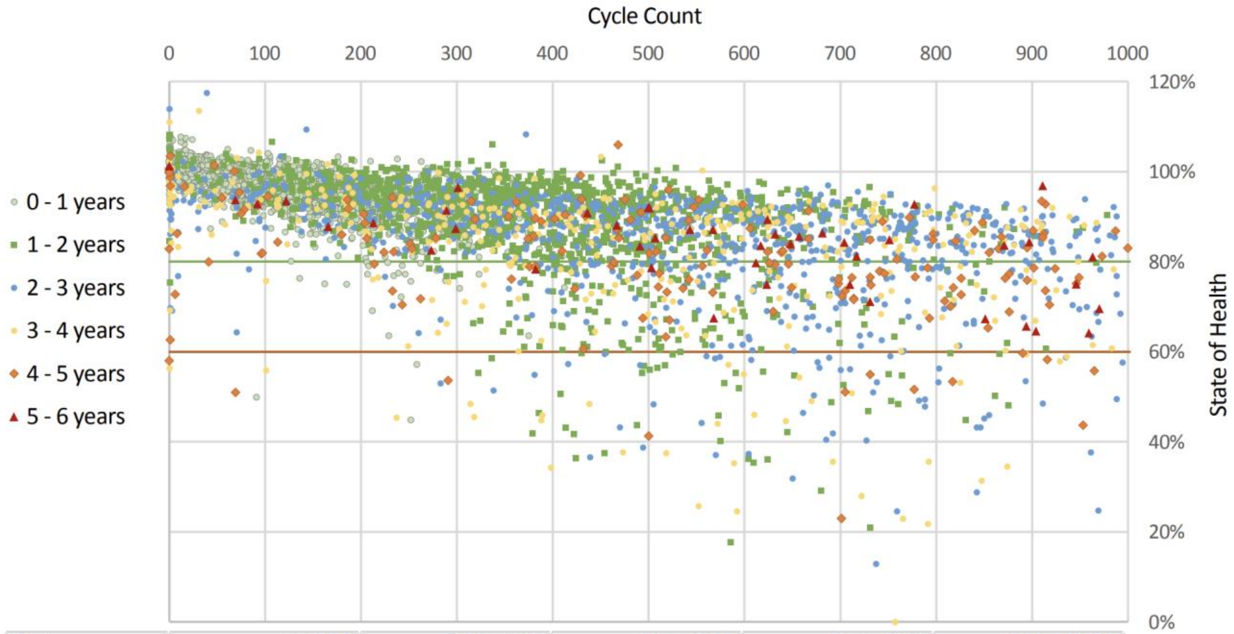
Technology	Gravimetric energy density [Wh/kg]	Volumetric energy density [Wh/L]	Charge time [C-rate][61]	Discharge time [C-rate][61]	Cycling (to 80% SOC)
LCO	160-210	340-580	0.7-1	1	500-1000
LFP	80-200	120-300	1	1-25	>2000
LMO	100-130	220-400	0,7-3	1-10	300-700
NCA	150-300	680-760	0,7	1	500
NMC	150–220	580-750	0,7-1	1-2	1000-2000
LTO	50-80	low	2-10	2-20	20000
SIB	160	n/a	n/a	n/a	n/a
SIB gen 2	200	n/a	n/a	n/a	n/a
Li-Sulphur	100-600	n/a	n/a	n/a	n/a
Li-air	800-894	n/a	n/a	n/a	n/a
oxide electrolyte	314-530	n/a	n/a	n/a	n/a
Sulfid electrolyte	500-567	n/a	n/a	n/a	n/a
Anode free	n/a	n/a	n/a	n/a	200
Si nanowire anode	365-430	875-1240	1/5	1/5	150-300
Si nanowire anothe	325-360	780-870	1	3	150-300
LiB High Si gr anode (NMC)	330	n/a	2	n/a	800
Li metal anode LiB	400-600	n/a	1/5	1/5	100-200
Li metal anode LiB	>400	n/a	10	10	> 200
Li metal anode LiB	400	780	1/3	1	700-800
LiBs with VACNT anode	160-600	n/a	High	high	high
Capacitor	lowest	lowest	higher	higher	20000
VACNT Capacitor	lower	lower	highest	Highest	>20000

Table 2: Performance data for all technologies

4.2 Lifetime of batteries

The performance of batteries can be quantified in different ways. It is necessary to consider durability in terms of cycles and in terms of high power or high energy demands for the different applications. The degradation of smartphone batteries (LCO) is presented in Figure 7 as a product of cycle count and age.

[61] Charge/discharge time = 1 hour/ C-rate (e.g. 1/5C is 5 hours, ¼C 4 hours, 1/3C 3 hours, 1/2C 2 hours,1C is 1 hour, 2C 30 min, 3C 20 min, 4C 15 min, 5C 12 min), hence, the higher C-rate, the shorter charge time.



Cycles	0 - 200	201 - 400	401 - 600	601 - 800	801 - 1000
Datasets (n)	1824	1174	887	504	247
SoH > 80 %	99%	92%	75%	64%	55%
SoH > 60 %	100%	99%	95%	90%	88%
SoH < 60 %	0,3%	1,4%	4,8%	10%	12%

Figure 7: State of health (SOH) of smartphone batteries, clustered into intervals of battery age in years, over the course of 1000 charging cycles in intervals of 200 charging cycles. The statistics below present the share of data points in each interval that have retained at least 80 % and 60 % SOH[62]

In batteries, cycle count and ageing causes capacity fade. The cathode chemistry has the highest influence on degradation caused by cycling, with the exception of graphite anodes with silicon content.

In Figure 8, Yuliya Preger et al[63] compares degradation of 3 different commercial 18650 LiB cells (LFP, NMC, NCA), depending on cycle characteristics. It is seen that LFP has much higher cycle times on all parameters. Furthermore, it is seen that, by limiting discharge to 20 percent and charge to 80 percent, NMC cell cycles can be more than doubled, while a discharge to 40 and charge to 60 percent is needed to see alike changes for NCA. Temperature wise LFP has - opposite to NMC and NCA - higher cycle time at lower temperatures, while NMC is more temperature susceptible than NCA. They all have longest cycle time at a charge rate of 2 C. The test data presented in Figure 8 is specifically representing one battery producer per chemistry, meaning that the possible dispersion of cycling times amongst different producers' cells is not reflected.

In general temperature, depth of discharge, level of charge, speed of charge and speed of discharge has most influence on battery cycle time.

A conclusion is that battery lifetimes can be extended by proper selection of battery technology to the purpose and typical usage situations.[64]

Another way of extending battery lifetime is through re-purposing i.e. where the battery can achieve a second life by being used for other purposes than the original purpose. E.g. if a battery for a mobile device has a capacity reduction of 50% and thereby does not fulfil the original purpose, it can be used for a stationary purpose. Typically, this is often mostly relevant for EV batteries used for grid storage for obtaining demand flexibility.

[62] Clemm, Christian & Sinai, Christoph & Ferkinghoff, Christian & Dethlefs, Nils & Nissen, Nils & Lang, Klaus-Dieter. (2016). Durability and cycle frequency of smartphone and tablet lithium-ion batteries in the field. 1-7. 10.1109/EGG.2016.7829849. Available at: https://www.researchgate.net/publication/312963977_Durability_and_cycle_frequency_of_smartphone_and_tablet_lithium-ion_batteries_in_the_field
[63] Yuliya Preger et al 2020 J. Electrochem. Soc. 167 120532 , Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions, https://doi.org/10.1149/1945-7111/abae37
[64] https://www.researchgate.net/publication/286242928_Lifetime_Analyses_of_Lithium-Ion_EV_Batteries

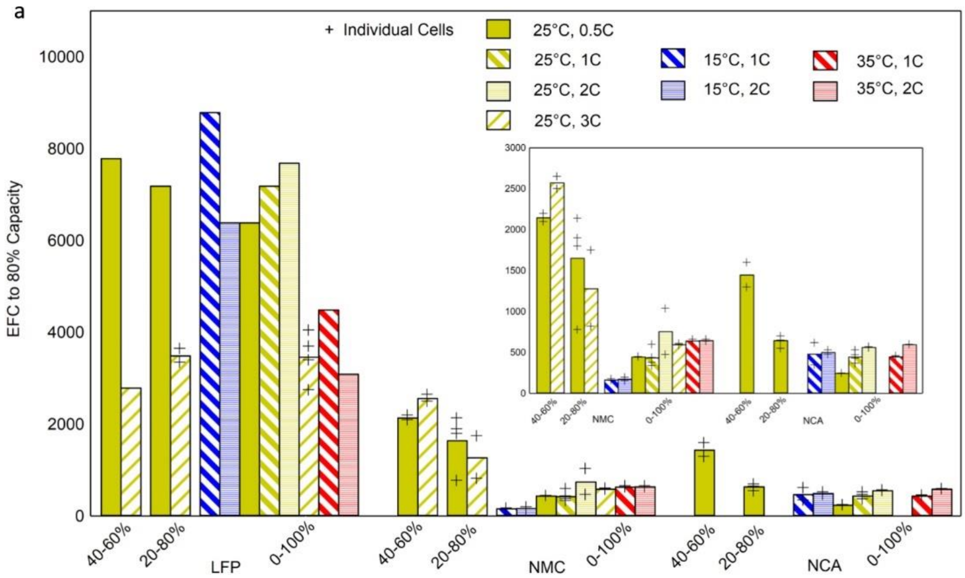


Figure 8: Cycling times before reaching 80% battery capacity at full cycles (meaning 100% charge/discharge) for LFP, NMC and NCA batteries, depending on temperature and charge rate (C). [65]

4.3 Sustainability performance

The main environmental impacts of batteries are often tied to their production and raw material phases of the life cycle. Most notably the energy (and thus CO_2 emissions) related to their production, and the use of scarce materials or materials sourced unethically. This chapter will therefore focus on the carbon footprint of battery production, the material sourcing and recycling.

4.3.1 Carbon footprint

The carbon footprint of batteries consists mainly in the CO_2 emissions related to battery production and raw material extraction, i.e. without accounting for the use phase and end-of-life phase of the batteries, and is thus not a life cycle comparison, but rather at cradle-to-gate comparison.

Figure 9 shows the carbon footprint for the known LiB chemistries that were listed in Section 3.2. The carbon footprint is given as GWP (Global Warming Potential) in kg CO2 emitted per Wh battery capacity.

[65] From Yuliya Preger *et al* 2020 *J. Electrochem. Soc.* 167 120532 , Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions, https://doi.org/10.1149/1945-7111/abae37.

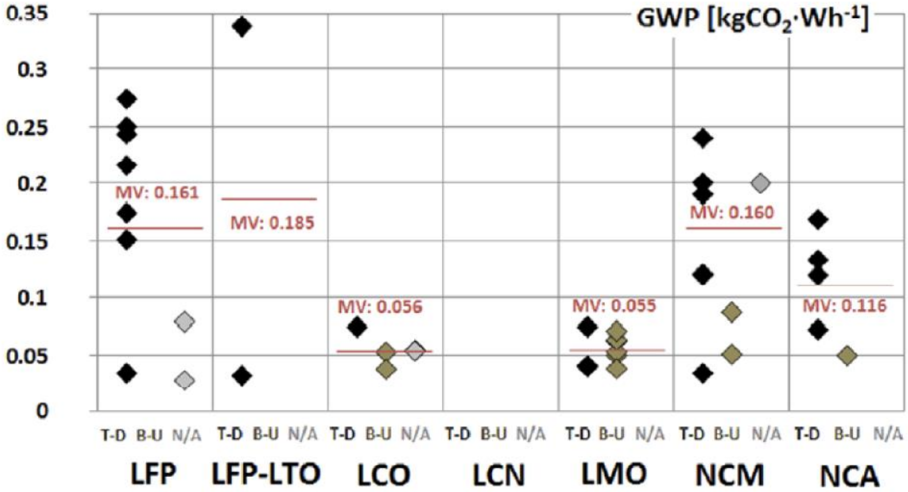


Figure 9: GWP results obtained for different battery chemistries, note that NMC also can be referred to as NCM as seen in the figure. T-D: Top-Down modelling; B-U: Bottom-up; N/A: not given. MV: mean value[66]

Comparing the mean GWP values, LFP and NMC is on par as highest contributors, with 161 and 160 kg CO_2/kWh respectively, NCA is 116, while LCO and LMO has the lowest mean values 56 and 55 kg CO_2/kWh respectively. It should be noted, though, that when comparing these data, lifetime of the specific chemistry should be taken into consideration as well, indicating how long time the battery will be able to supply electricity for its given application.

Higher silicon percentage content in the anode will drive the overall GWP down for these particular chemistries, however, due to large expansion (about 300%) when charging, this might result in lower battery lifetime.

GWP for future technologies was not available, but this has to be accounted for when choosing future battery technology paths. Future growth in recycled raw material use in the battery industry will help lower the CO_2 footprint as well[67].

As seen in Figure 9, the data on LCO, LMO, and to some extent NCA has small deviation from the mean value, while the data for LFP and NMC (NCM in the figure) shows higher deviation. This can to a large extent be explained by the variation in geographic location of battery production, as these battery types are produced in more different countries/word regions. This in turns lead to differences in the carbon intensity of electricity grid supply in the production of the batteries, giving this spread in carbon footprints of the batteries.

Today, batteries are almost exclusively made from virgin materials, however, increased recycling rates, especially of materials with high energy demanding extraction process, and the development within EU on reducing the carbon footprint of batteries by using more renewable energy sources for production, especially in the Nordic countries, can significantly lower the carbon footprints reported in Figure 9[68]. In December 2020, the European Commission published its proposal for a Regulation on Batteries and Waste Batteries[69]. The proposed Regulation will introduce new requirements for batteries placed on the EU market, including provisions on carbon footprint, recycled content, recycling efficiencies, materials recovery targets and due diligence[70]. The European Parliament backed the proposed measures during the plenary session in March 2022 and will continue the negotiations with EU governments[71].

[66] Peters, Jens F, Manuel Baumann, Benedikt Zimmermann, Jessica Braun, and Marcel Weil. 2017. “The environmental impact of Li-Ion batteries and the role of key parameters – A review.” Renewable and Sustainable Energy Reviews 491-506
[67] Batteries in the Nordics - Change for circularity, 2020.
[68] www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf
[69] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798
[70] https://nickelinstitute.org/en/blog/2022/february/eu-batteries-regulation-where-do-we-stand/
[71] https://www.europarl.europa.eu/news/en/headlines/economy/20220228STO24218/new-eu-rules-for-more-sustainable-and-ethical-batteries

4.3.2 Sourcing of materials, especially rare earth metals

Sourcing of materials for batteries, especially the increasing demand it puts on rare earth metals such as cobalt, is not only an environmental sustainability issue, but also very much a social sustainability issue.

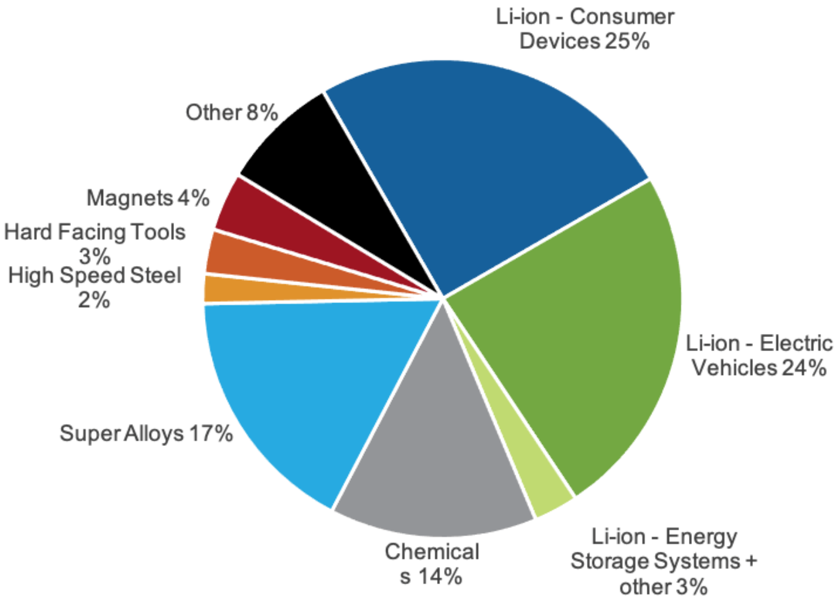


Figure 10: 2021 global cobalt consumption distributed on sectors.[72]

As seen in Figure 10 cobalt consumption from batteries for portable devices, is 25% of the global market, while consuming the same amount of cobalt as EV battery production, even though the EV battery industry produces over 5 times more kWh batteries

Cobalt, as the prevailing example, is sometimes mined in hazardous conditions, and child labour is a common occurrence in especially cobalt Artisanal and Small Scale Mining (ASM)[73]. Cobalt is mostly extracted as a by-product when mining nickel and copper, but as ASM growth is driven mostly by price, the share of cobalt mined from ASM has been growing the later years due to increasing battery demand. Over 50 percent of global cobalt supply is mined in DR Congo. The European Commission completed a study in 2020, regarding the feasibility of introducing sustainable sourcing requirements through supply chain due diligence for batteries[74]. This focused primarily on cobalt, but the principles can also be transferred to other rare earth materials. This could be manganese which is mined in countries (South Africa, Gabon and China) where ASM is a common mining method.

[72] www.cruxinvestor.com/articles/the-ultimate-guide-to-the-cobalt-market-2021-2030f
[73] https://www.dol.gov/agencies/ilab/combatting-child-labor-democratic-republic-congos-cobalt-industry-cotecco
[74] https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/EDbatteryFollowupWP4finalpreprint.pdf

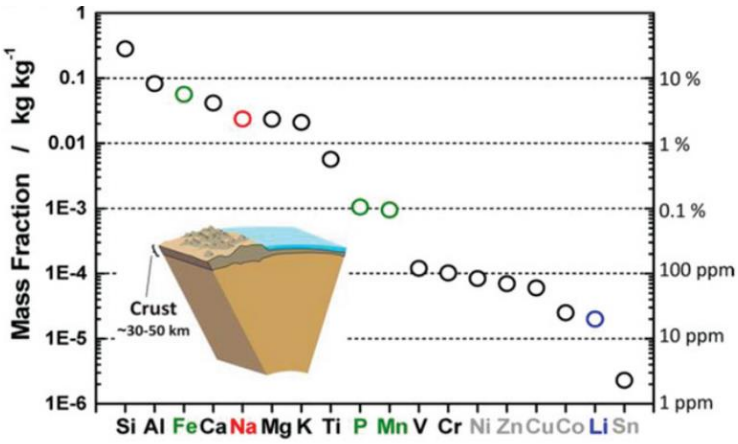


Figure 11: Showing earth crust elements and abundance[75]

In Figure 11 earth crust mass fraction of elements used in known and future battery technology is shown, giving an indicator for which materials from an abundance perspective would be most attractive for batteries. Sourcing is also affected by geopolitical concerns of location with regards to raw materials like lithium, nickel, cobalt, manganese and graphite should also be taken into consideration.

Regarding lithium supply for the global battery market, demand and supply is balanced on short term, but the projected EV growth, and the corresponding demand for LiB, is analysed to create supply deficits. In most scenarios demand would result in resource depletion before 2100. EU added lithium to their list of Critical Raw Materials (CRMs) for the first time in 2020. CRMs are defined as raw materials of high importance to the EU economy and of high risk associated with their supply[76], however this does not address the global resource availability.

To address this concern, efforts are needed to create global recycle systems, but also development of higher performance LiBs, and alternative chemistries is needed, to lower Li demand[77]. The mentioned efforts will have implications on battery technology development for portable devices. Though when comparing the expected growth of the portable device segment with the EV segment, EVs will lead to a much higher increase in global battery demand, and therefore the portable device segment will not be the restraining segment regarding resource depletion[78].

4.4 Cost

The cost of LiB is expected to decrease further over time due to technology development, as seen in Figure 12. This is despite some raw materials are limited, which generally would have resulted in higher prices due to consideration on the supply and demand.

The Covid-19 pandemic, has, however, lead to a price increase in 2021[79] due to the increase in price of raw materials[80], as well as supply chain issues decreasing the supply. Raw material price increases will affect all battery types (at least those relying on lithium) but is not foreseen to change the overall trend towards increasing demand for mobile devices vs. stationary devices.

[75] Advanced Energy Materials - 2020 - Durmus - Side by Side Battery Technologies with Lithium-Ion Based Batteries
[76] https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
[77] Greim, P et al, Nature communications, Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation, 2020, p.8
[78] https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/ED_Battery_study_Task2_V21_final.pdf, p. 41-42.
[79] https://www.greencarcongress.com/2021/10/20211030-benchmark.html
[80] https://www.bloomberg.com/news/newsletters/2021-09-14/ev-battery-prices-risk-reversing-downward-trend-as-metals-surge

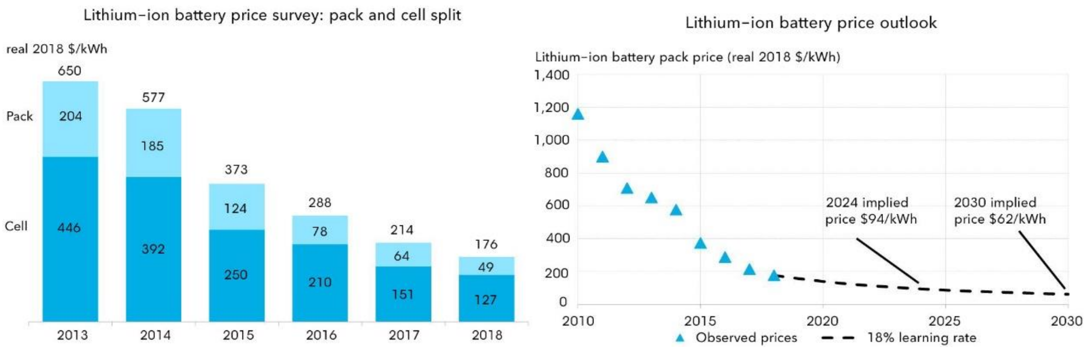


Figure 12: Left: Historical price development, with car battery pack and cell part differentiation, volume weighted average. Right: forecast for Li-ion battery pack price. Source: both from Bloomberg NEF 2018[81].

In Figure 12, both historical and predicted price of LiB for EVs is presented. The different commercialized battery chemistries are included on a volume weighted average. Probably the forecast will be affected by the recent EV trend of moving lower range car battery chemistry from NMC to LFP, led by Tesla and VW[82]. Future LFPs offer a lower price, by exchanging costly nickel and rare manganese and cobalt, with high abundant iron and phosphorus (see Figure 11), at the price of a lower energy density. The safer LFP chemistry allows for more compact and cost-efficient cell structures, and minimal battery pack expenses compared to NMC.

Looking into LFP application for portable devices, the almost double volumetric energy density of LCO, makes it a hard case for laptops, smartphones and wearables. Though with future advances in anode materials like increased silicon content, LFP will probably soon reach parity with today's LCO performance (which will be enhanced as well with new anode materials). But with its higher discharge rate than NMC, it is already used in power tools, and could have more adoption in battery driven vacuum cleaners, e-scooters and e-mopeds, if the product allows for the 30% weight increase, and double volume.

Price predictions for future technologies can be challenging. Price mostly depends on choice of anode and cathode chemistry, choice of electrolyte type (liquid, polymer, solid state) and chemistry (ceramic, solid state electrolyte), the weight distribution of these, and manufacturing cost which partly is dependent on the before mentioned parameters, (for instance processing of Li metal anode requires inert atmosphere) but also the projected market size. With that in mind future technologies, which has not yet settled on the above parameters, cannot be predicted properly.

Mauler et al.[83] has reviewed 53 different LiB price forecasting studies, and an excerpt of their data is seen in Figure 13. In general, the high variances are due to uncertainties with regard to solid electrolyte, lithium metal foil for anode prices, and excess lithium percentage, which varies from 50-300%.

The presented data shows sulphuric solid electrolyte as the only SSB with potential to outperform LiB price, while LSB forecast average (135 \$ kWh^{-1}) is just below HE-NMC (139 \$ kWh^{-1}) which has the best performing LiB average, while LAB has the lowest forecast average (104 \$ kWh^{-1}) for all presented data.

The recent anode free technology[84], has not yet been subject to price forecasting and is therefore not part of the study, but the absence of lithium foil and excess lithium shows promise of lower price levels than the presented.

Market price levels of LiBs has already dropped below the average forecasted data in Figure 13.

[81] https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/
[82] https://oilandgas-investments.com/2021/investing/lfp-batteries-are-winning-the-ev-race-but-wheres-the-ex-china-supply/, visited March 2022.
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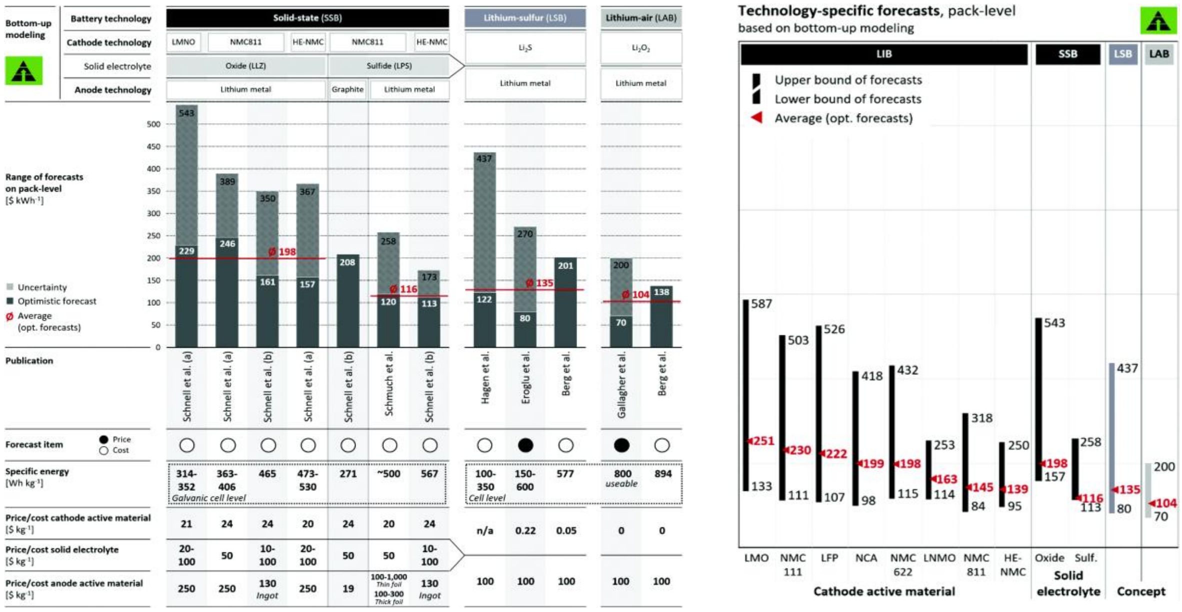
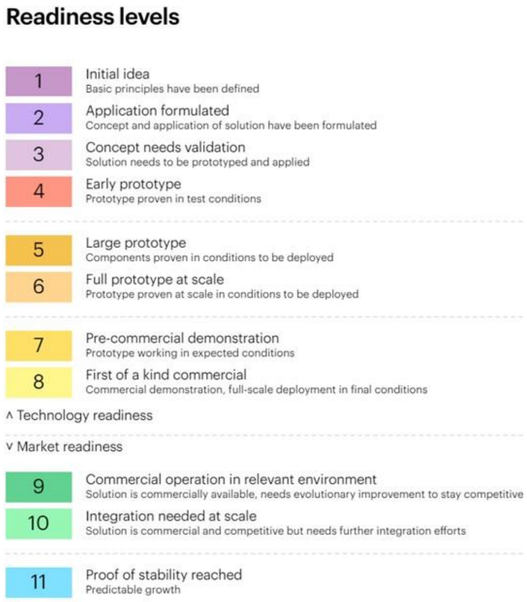


Figure 13: Left: Price projections for solid state batteries (SSB), lithium sulfur (LSB) and lithium air batteries (LAB). Right: Pack level price prediction for LiB, SSB, LSB and LAB. Both bottom-up modeling[83].

4.5 Maturity for Commercialization

The maturity for commercialization amongst the technologies covered in the report, is presented through the Technology Readiness Level (TRL) framework.



Readiness level	Technology
9-11	LiB
7-8*	LiB Li metal anode
5	Li metal Solid state electrolyte
4	Li Sulphur
1-2	Li air
3-4 (8 CATL*)	Li sodium (Na+)
3*	LiB Anode free Li
4*	VACNT LiB
6-7*	LiB + high Si Gr anode
9-11*	Supercapacitors
7*	VACNT super caps
5 (8-9*)	LiB + silicon anode
2	Multivalent ions

*Figure 14: Technology readiness level of the battery technologies described in the report. Values are taken from IEA technology catalogue[85], while * values are estimations from the research presented in the report. Source left hand-side[85].*

[85] www.iea.org/articles/etp-clean-energy-technology-guide

5 Conclusion

The innovation in battery technology is moving at pace, both in terms of improving on existing technologies such as optimising lithium-Ion batteries, and in terms of developing new battery technologies from the bottom up, such as sodium batteries. While battery technology receives a lot of funding[86], it still takes a long time for a new or improved battery technology to reach the market (around 20 years)[87]. Therefore, despite a large effort from research facilities and private corporations, the lithium-Ion technology still prevails in mobile devices and EVs, and some manufacturers even move towards existing technologies that were thought to be outdated, rather than bet on new technologies for the short term, as seen with the NMC technology.

The following policy recommendations are given as high-level focus points for development of the battery sector in the future, without dictating specific technologies, or focusing on the technical characteristics of the batteries. Instead, focus is on market and environmental aspects.

Some of the main issues with the current battery technologies (mainly lithium based) are related to the sourcing of materials. Primarily, a shortage of battery raw materials is foreseen in the mid-2020's[88], which is related to the rapidly increasing demand combined with scarce resources, and supply chains being controlled to a large extent by mainly China. Secondly, the extraction of some of the materials, of which cobalt is the most mentioned, is related to severe social and health issues as well as environmental damages.

Based on the findings in this study, the recommendations are therefore to:

- **Make a policy effort to use better battery technologies than LCO in small portable devices**
  LCO has been surpassed in regard to volumetric and gravimetric energy density by other LiB technologies with much lower or no cobalt content (LCO cathode ~ 60%, NMC 811 under 2010%), but LCO is still the prevalent battery for the smaller portable devices.

- **Ensure technology neutrality**
  While technology neutrality is a widely accepted principle within law making, it is especially important for developing sectors, such as the battery sector, as not even researchers at this point know, which technologies will prevail in the future, and it therefore important to ensure that no legal barriers unintendedly reduce the possibilities. It is very likely that the future energy market will be made up of several battery technologies co-existing, rather than one dominating technology (such as LiBs today).

- **Ensure due diligence or other ethical sourcing principles are introduced for problematic resources**
  This is in line with the EU study on Ecodesign and Labelling of batteries (part of the basis for the proposed revised EU Battery Directive), where due diligence was proposed as a policy tool to decrease the issues related to e.g. cobalt mining. Given the scarcity of resources, such policies will only have the required effect if implemented to a larger extent that just in the EU.

- **Focus research funds on batteries with low or no use of CRMs, and raw materials that are scalable**
  This can for example be sodium batteries, or other readily available materials. This will eliminate some of the issues related to mining CRMs such as cobalt, and supply issues related to e.g. lithium, and possibly split the control of supply chain on multiple players, rather than a few.

- **Limit the environmental impact of battery production through LCA or carbon footprint requirements**
  Besides the ethical aspects related to mining of some raw materials for batteries, environmental impacts can be regulated e.g., through requirements set on the bases of LCAs (Life Cycle Assessments). This can for example be the PEF (Product Environmental Footprint) methodology, or other aligned methodology to ensure comparability of results. For simplification the requirements can also be set on carbon footprint, however, it is important to note that mining for metals (primary raw materials for batteries) is associated with toxicity impacts, and GWP (Global Warming Potential) might thus not be the only thing relevant to mitigate.

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[86] https://www.forbes.com/sites/rrapier/2021/02/06/funding-for-battery-technology-companies-exploded-in-2020/
[87] https://www.dtu.dk/english/news/2020/09/eng-hvorfor-har-vi-travlt-med-at-udvvikle-nye-batterier?id=c0d44699-69f3-4fd3-96e8-3155f4e8d80a, https://battery2030.eu/research/roadmap/
[88] Global Data report: https://store.globaldata.com/report/tech-media-and-telecom-predictions-market-analysis/

No matter which approach, it is important to take into account the lifetime of the batteries when comparing upstream impacts.

- **Focus on supporting recycling and other circular economy approaches**
  Increasing lifetime through BMS systems: Battery Management Systems play an important role in battery health and thus lifetime. BMSs can balance the numerous interacting battery performance parameters, to achieve the best performance while optimizing lifetime of the battery. It should be noted that optimizing lifetime of batteries give rise to a number of trade-offs, which should be kept in minds. For example, focusing on lifetime, with the purpose of not reducing capacity to a less then acceptable level (defined by users), might result in producers using larger batteries to comply with any requirements, thus resulting in higher resource consumption, rather than lower.

  Promote recycling possibilities and technologies: One way to mitigate some of the impacts of mining raw materials, including lowering the carbon footprint, is to recycle the materials. However, today most materials from batteries are difficult to recycle, especially the lithium, so research efforts are needed to develop efficient recycling.

  Promote design for recycling: In order for efficient recycling, the design of the batteries is also important, both regarding their material composition, as some materials might be easier to recycle than others.

  Promote re-purposing: Re-purposing through using the battery or the battery cells for a different purpose than the original purpose will extend the lifetime.

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