



Geological Survey of Finland

Unit: Circular Economy Solutions

Place of business: Otaniemi, Espoo, Finland

August 26, 2022

# Literature survey of potential raw materials for rechargeable batteries

## *BATCircle2.0 Project Report – WP1.5 Task 1*

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August 26, 2022

**GEOLOGICAL SURVEY OF FINLAND****DOCUMENTATION PAGE**

Date / 26.08.2022

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<p>Title of report</p> <p>Literature survey of potential raw materials for rechargeable batteries</p>	
<p>Abstract</p> <p>The transition to electrified transport and energy storage is required to meet global climate change carbon dioxide reduction goals. Such a system change will require vastly increased production volumes of rechargeable batteries, for use as the power source for electrified transport, and as static energy storage for grid balancing and to compensate for the partially intermittent nature of cleaner electricity sources such as wind and solar power. From a material availability viewpoint, the required increases in rechargeable battery production may be hampered by bottlenecks in the supply chain resulting from a lack of stockpiled materials, and/or from the limitations of future material production capacities (both in terms of known resources of metals or other minerals, and the mineral reserves – the amount of these resources that can be economically extracted).</p> <p>Similarly, production may be limited by the costs of those raw materials that are available in sufficient quantities, especially if their prices rise with increased demand. In this report, we examine the range of raw materials required for current and potential future rechargeable battery chemistries. Different usages for rechargeable batteries require different performance parameters. These include energy density (which controls final battery weight and size), safety, charge and discharge speed, lifetime number of charge/discharge cycles etc. These performance parameters also vary with different battery chemistries, and so different usages can be matched with specific battery types.</p> <p>Based on current rechargeable battery production trends, we predict that over the next ten years a moderately diverse ecosystem of around eight or nine different rechargeable battery chemistries will develop. These will partly be tailored towards different applications, and result in an increase in the range of raw materials used compared with the present day. However, we suggest lithium-ion based chemistries will capture an even larger proportion of the market than currently. We therefore identify lithium as the primary raw material of concern in terms of availability, with vanadium as a secondary but considerably reduced concern.</p> <p>Careful balancing of economic, environmental and performance parameters will be required to successfully achieve the desired, drastically increased future production goals for rechargeable batteries. By taking into account raw material availability at all steps of the battery production and recycling process, and incorporating this information as another set of parameters to be balanced, the shift to an electrified future can be better managed.</p>	

August 26, 2022

Keywords <b>Battery minerals, critical raw materials, lithium-ion, lithium, battery chemistries, recycling, electric vehicles, energy storage</b>			
Report serial <b>GTK open file work report</b>		Archive code <b>32/2022</b>	
Total pages <b>32</b>	Language <b>English</b>	Price <b>N/A</b>	Confidentiality <b>Public</b>
Unit <b>Circular Economy Solutions Unit</b>		Project code <b>50404-4021026</b>	
Signature/name   <b>Ian Corfe</b>		Signature/name   <b>Alan R Butcher</b>	

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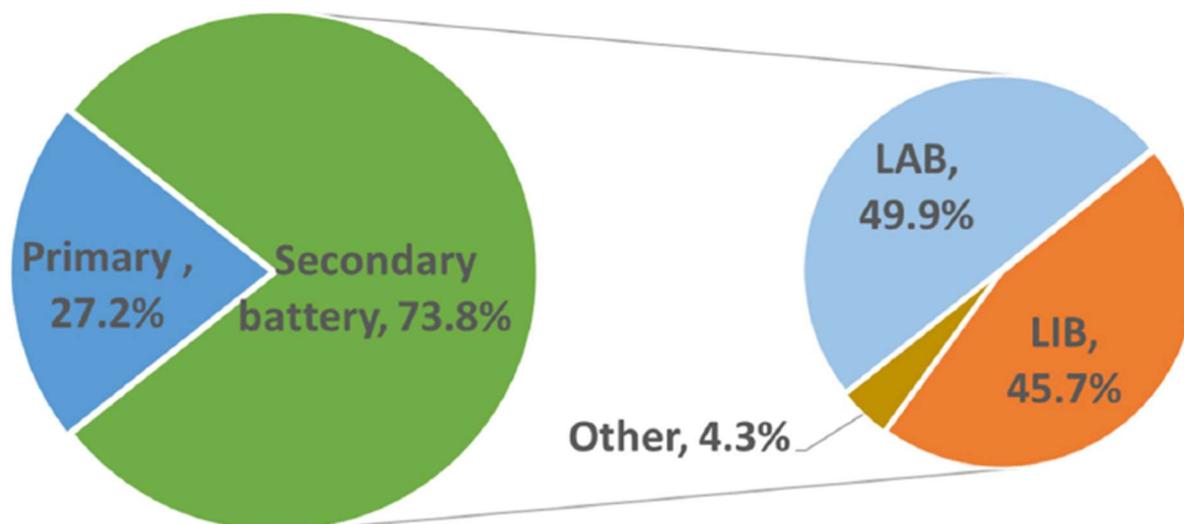
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## 1 INTRODUCTION

There is a broad consensus that rechargeable batteries are a key technology in the transition of transport and energy storage to a greener and lower CO<sub>2</sub> emitting future (IEA, 2021a; IEA, 2021b; IPCC, 2022). Their past and current use has mainly been in consumer electronics of all kinds, medical equipment, construction devices such as power tools, satellites, and as low voltage ancillary power providers for vehicles. However, it is widely predicted that rechargeable batteries will be required in increasingly large amounts for two main applications; as the main power source for electric vehicles of all sizes, from e-bikes and e-scooters through electric motorbikes and cars to, potentially, lorries/trucks, ships, trains and aeroplanes; and as power storage systems to balance electrical grids and capture and release energy from intermittent clean energy sources such as solar and wind, at local and national scales (IEA 2021a; IEAE 2021b; Michaux 2021).

Most of the current global rechargeable battery production, by watt-hour (Wh) energy storage capacity production amount, is of lead-acid batteries (Avicenne Energy 2019; Zhao et al. 2021b; **Figure 1**). These have been around for approaching 200 years, though they are still being slowly improved. Lead-acid rechargeable batteries are relatively cheaply produced and easily recycled, and widely used as backup power systems, grid and off-grid energy storage systems and, since they are capable of producing the required relatively high surge currents, automotive systems. However, for many applications they have the disadvantages of being heavy and having low energy storage density. Because of these negatives, and in particular in the light of the requirements for light, high energy storage density batteries in the electrification of the transport sector, lead-acid batteries are expected to soon be overtaken by lithium-ion batteries in terms of total global storage capacity production amount (Duffner et al. 2021).



**Figure 1.** Worldwide market share of battery types (left, primary= single use, secondary= rechargeable) and chemistries (right, LAB = lead acid, LIB = lithium-ion). Data from 2019. Source: Zhao et al. 2021b.

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Lithium-ion batteries of the currently made type were first envisaged in the 1970s and 1980s, with prototypes appearing in the mid-1980s and commercial cells first produced in the early 1990s (Scrosati 2011). Following almost 40 years of research, in comparison to other rechargeable battery chemistries lithium-ion batteries offer a combination of high mass- and volume-energy densities, and relatively well understood and generally satisfactory performance in terms of safety, durability and number of lifetime charge/discharge cycles. However, within the umbrella of lithium-ion batteries, numerous alternative chemistries exist and are in commercial use, especially for the cathode materials (Manthiram 2020). Considerable research is ongoing into the development and commercialization of new cathode and anode chemistries for lithium-ion batteries.

As well as lead acid and lithium-ion batteries, which make up the vast majority of currently produced rechargeable batteries by energy capacity, a wide range of currently available, in development, and theoretical batteries that are not lithium-ion based exists (Grey & Hall 2020). Because of their varying properties, some battery chemistries may be more suitable for specific use-cases than others. For instance, backup power storage batteries, grid balancing batteries and intermittent clean-energy storage batteries can in most cases be relatively heavy and large (i.e., with low energy density), whereas batteries for personal medical devices, health monitors, wearable electronics etc. are required to be lightweight and small (with high mass- and volumetric-energy density). Similarly, other parameters of rechargeable batteries such as charging speed, durability, total lifetime cycle number etc. can be targeted towards the requirements of specific applications. Finally, the benefits of producing a more diverse rechargeable battery ecosystem include:

1. The economics of batteries (since alternative battery chemistries may be cheaper than lithium-ion systems, either due to the raw material requirements, the production methods, or since most battery economics are based on a cost per kWh basis, the energy densities of the respective chemistries - Schmuch et al. 2018; Hsieh et al. 2019; Turcheniuk et al. 2021).
2. Material availability (since a number of the materials, especially the metals, in current lithium-ion batteries are classified as critical raw materials, and it is uncertain whether there are enough reserves or production capacity to cover the demands of full-scale electrification of transport and energy storage - Olivetti et al. 2017; Greim et al. 2020; Heijlen et al. 2021; Mudd 2021; Turcheniuk et al. 2021; Zeng et al. 2022).
3. The environment (since there is a time-component to electrification plans for reducing CO<sub>2</sub> production which will be affected if there are raw materials shortages resulting in production lower than demand and behind schedules for carbon dioxide emissions reductions, some chemistries are particularly toxic in the short or long term, different battery chemistries could be designed with recycling built in from the start, and the extraction and refining of different minerals and metals has varying environmental impact - Zhang et al. 2018; Harper et al. 2019; Yang et al. 2021; Zhao et al. 2021b).

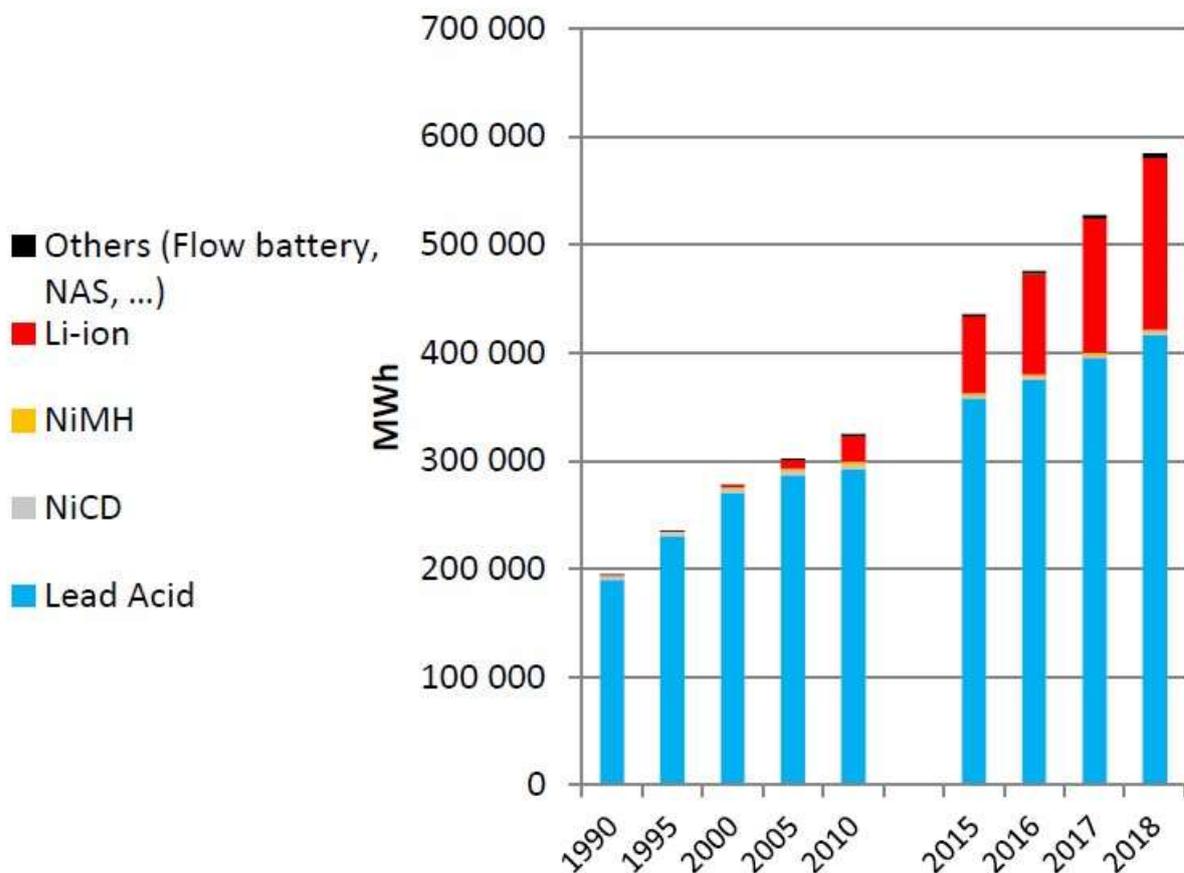
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In this review, we examine the range of raw materials required for the anticipated ramping-up of rechargeable battery production and consumption, especially those of a geological/mineralogical nature. This is undertaken in the light of the potential for alternative battery chemistries to be used to reduce reliance on the current, relatively narrow range of metals and minerals used in the dominant lithium-ion battery chemistries. Because of the vast and increasingly large proportion of rechargeable battery production used for transport and static energy storage when compared to the volumes required for e.g. personal electronics or medical instruments and devices, we concentrate on the former. This report is an output of Work Package WP1.5 ('Raw materials for alternative battery chemistries') of the Business Finland funded project BATCircle2.0. The aims of BATCircle2.0 are principally to find various means of adding value to the Finnish battery metals sector at all stages of the value chain, from mineral exploration and extraction, through material processing, to battery production and eventually recycling.

## 2 LEAD-ACID BATTERIES

Lead acid batteries have been for decades the most produced rechargeable battery in terms of capacity produced per year (Avicenne Energy 2019; Zhao et al. 2021b; **Figure 2**), though they have just now been caught up and potentially overtaken by lithium-ion batteries (Duffner et al. 2021). They use the negatively charged anion  $\text{HSO}_4^-$ . Their advantages are cost, material availability and recyclability (98% or more of the lead from rechargeable lead-acid batteries is currently recycled, Ballantyne et al. 2018; Zhao et al. 2021b); their disadvantages are very low energy capacity, both volumetric and gravimetric, compared with lithium-ion batteries, and high toxicity of the lead itself. Lead-acid batteries are principally used in the automotive ancillaries and emergency power supply industries. Moderate development in recent decades has increased their suitability for static energy storage systems, but because of their low energy density they are less suitable for giant storage and grid balancing projects than lithium-ion batteries (May et al. 2018). Similarly, because of increasing energy density and decreasing costs of lithium-ion batteries in recent years, the cost/kWh of lead acid batteries is now higher than lithium-ion, making them uneconomical. However, as a mature battery chemistry, lead-acid could be used as large-scale static energy storage in particular 'sweet-spot' circumstances and potentially production could be ramped up if the demand for lithium-ion batteries cannot be met due to e.g. critical metal shortages or price increases. The principal materials for lead-acid batteries are lead (Pb) anodes, lead dioxide ( $\text{PbO}_2$ ) cathodes, and sulfuric acid liquid electrolyte ( $\text{H}_2\text{SO}_4$ ).

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**Figure 2.** Market share of rechargeable batteries, 1990-2018. Source: Avicenne Energy 2019.

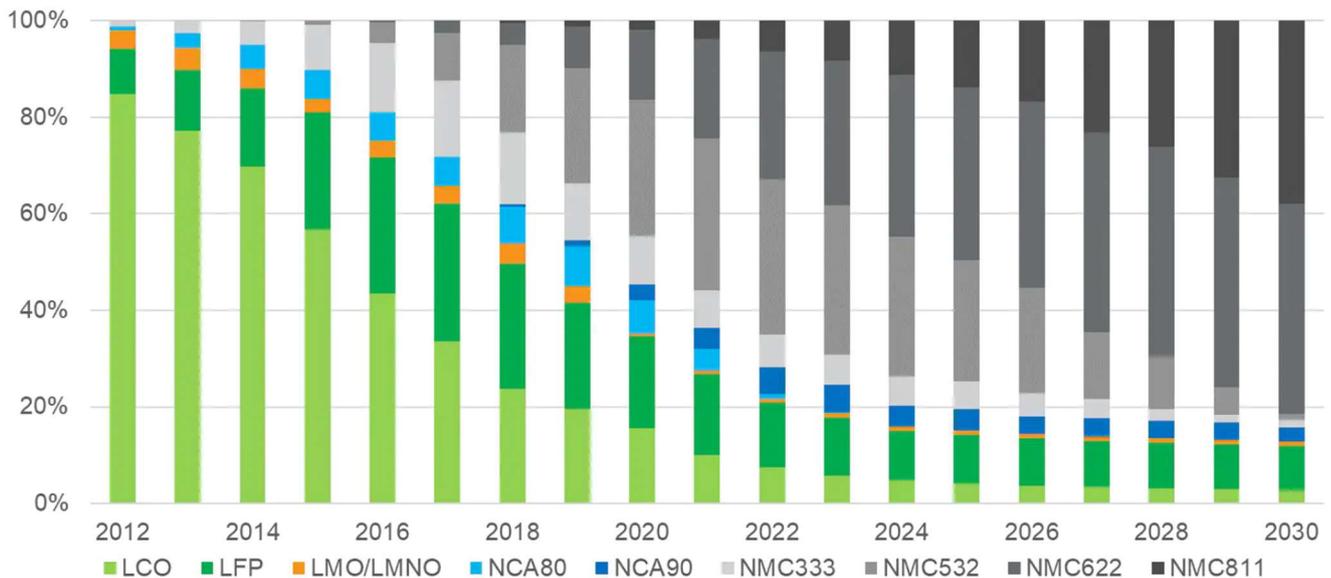
### 3 LITHIUM-ION BATTERY CHEMISTRIES

#### 3.1 Cathode

##### 3.1.1 Past and present lithium-ion battery cathode chemistries

Over the 31 years since lithium-ion rechargeable batteries were first commercialized in 1991, a wide range of different cathode chemistries have been used (Manthiram 2020; Wu et al. 2020) (**Table 1**). The earliest safe commercial lithium-ion batteries used Lithium Cobalt Oxide (LCO,  $\text{LiCoO}_2$ ) cathodes. Lithium Manganese Oxides (LMO, with various lithium, manganese, oxygen ratios) were introduced and offered cost advantages over LCO but also lower specific energy capacity (in terms of volume and mass) and haven't been widely used. Over the last decade, three main cathode chemistries have caught or overtaken LCO in terms of annual production by GWh – Lithium Iron Phosphate (LFP,  $\text{LiFePO}_4$ ), Lithium Nickel Manganese Cobalt Oxides (NMC, with various nickel:manganese:cobalt ratios) and Lithium Nickel Cobalt Aluminium Oxides (NCA, with various nickel:cobalt:aluminium ratios) (IHS Markit 2021; **Figure 3**).

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**Figure 3.** Past and predicted future global market share for different lithium-ion battery cathode chemistries. For abbreviations, see text. NCA numbers = nickel %; NMC numbers = relative proportions of nickel, manganese, cobalt. Data from 2020. Source: IHS Markit 2021.

Although LFP has lower theoretical specific energy capacities (both volumetric and gravimetric) than LCO, and NMC and NCA higher specific energy capacity than LCO (Zubi et al. 2018; Wu et al. 2020) (**Table 1**), production volumes don't reflect these metrics but instead other parameters. LFP uses abundant and cheap metals and other elements, and offers high recharge cycle numbers and good thermal safety and durability (Severson et al. 2019). Because of the safety characteristics of LFP batteries, it is also possible to fill an electric vehicle battery pack with more active material and less packaging, safety and cooling equipment. It has been estimated that LFP cell-to-pack designs allow 85-90% of the pack weight to be made of cells, while the equivalent for NMC battery packs with modular construction is 60-65% (PushEVs 2020). This difference allows LFP batteries to partly overcome their inherently lower gravimetric specific energy capacity. LFP is therefore well suited to both static energy storage and cheaper, lower range electric cars, and as such has recently become the most manufactured lithium-ion battery cathode chemistry in China, which is the largest lithium-ion battery producer worldwide – almost twice as much capacity production of LFP than other lithium-ion chemistries is currently being made (NDRC 2022).

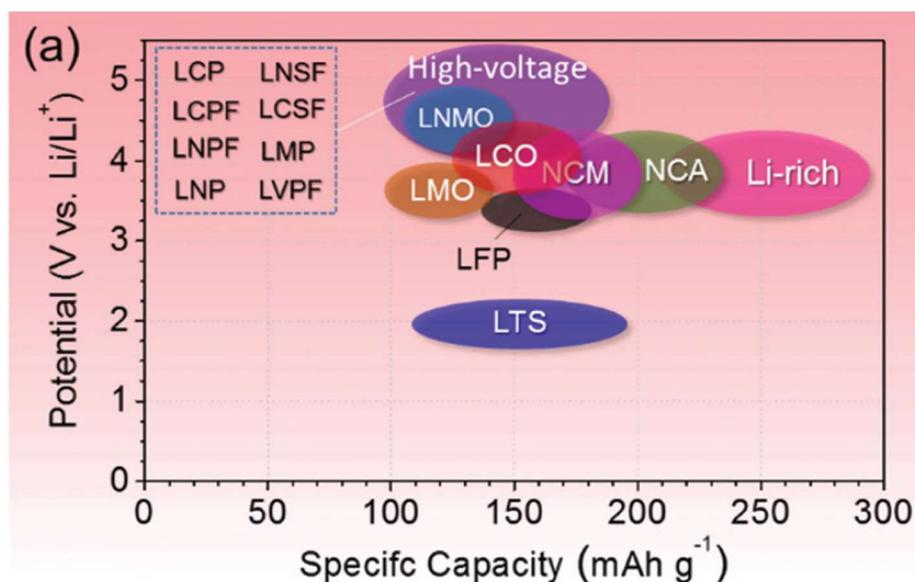
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**Table 1** Properties of cathode materials (modified from Wu et al. 2020)

Active materials	Specific capacity mA h g <sup>-1</sup> /mA h cm <sup>-3</sup>	Potential (V vs. Li <sup>+</sup> /Li)
Currently commercially available		
LiFePO <sub>4</sub> ( <b>LFP</b> )	170/612	3.4
LiCoO <sub>2</sub> ( <b>LCO</b> )	140/714	3.8
LiMnO <sub>2</sub> ( <b>LMO</b> )	140/590	3.4
High-voltage LiCoO <sub>2</sub> ( <b>LCO</b> )	185/944	3.95
LiNi <sub>0.8</sub> Co <sub>0.1</sub> Mn <sub>0.1</sub> O <sub>2</sub> ( <b>NMC<sub>811</sub></b> )	200/930	3.8
LiNi <sub>0.8</sub> Co <sub>0.15</sub> Al <sub>0.05</sub> O <sub>2</sub> ( <b>NCA</b> )	220/979	3.6
High voltage		
LiMnFePO <sub>4</sub> ( <b>LMFP</b> )	171/?	4.1
LiNi <sub>0.5</sub> Mn <sub>1.5</sub> O <sub>4</sub> ( <b>LNMO</b> )	147/625	4.7
LiNiPO <sub>4</sub> ( <b>LNP</b> )	169/657	5.1
LiCoPO <sub>4</sub> ( <b>LCP</b> )	167/618	4.8
Metal halides		
CuF <sub>2</sub>	528/2002	3.55
FeF <sub>3</sub>	712/2196	2.74
CoF <sub>2</sub>	553/2038	2.80
NiF <sub>2</sub>	554/2040	2.96
CuCl <sub>2</sub>	399/1115	3.17
FeCl <sub>3</sub>	496/1172	2.83
Chalcogen elements and lithium chalcogenides		
S	1675/1937	2.28
Li <sub>2</sub> S	1166/1937	2.28
O <sub>2</sub>	1675/2698	2.96
Li <sub>2</sub> O <sub>2</sub>	1168/2698	2.96

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NCA has previously had the highest specific energy capacity of widely available lithium-ion batteries, but owing to price and thermal stability concerns has only roughly matched LCO in production volumes (IHS Markit 2021; **Figure 3**). NMC meanwhile has become the most produced cathode chemistry worldwide though may soon be overtaken by LFP. Successive NMC variants with decreasing proportions of manganese and cobalt coupled with efficiencies from increasing volumes of production have led to cost reductions, and specific energy capacity increases have placed it just above NCA in these metrics in the latest iterations (Manthiram 2020; Wu et al. 2020; **Figure 4**). Currently, the market appears to be diverging in two directions with NMC capturing the higher cost, higher specific energy capacity part and LFP the lower cost, lower energy part. Both have similar market shares, accounting for the vast majority of all lithium-ion batteries produced between them, though LFP production volumes are accelerating more rapidly than NMC (NDRC 2022).

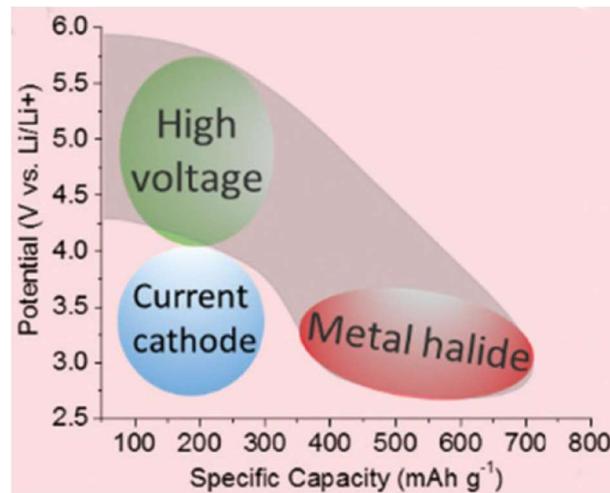


**Figure 4.** Specific energy capacity against potential voltage for the main current and proposed lithium-ion battery cathode chemistries. For abbreviations, see text. Source: Wu et al. 2020.

### 3.1.2 Future lithium-ion battery cathode chemistries

Two main directions of cathode chemistry research are being followed in the pursuit of improved, higher energy storing lithium-ion batteries of the future (Manthiram 2020; Wu et al. 2020). The first of these aims to increase the potential difference (i.e. the voltage) (Kawai et al. 1999; Ling et al. 2021), the second the specific energy capacity (He et al. 2021; Zhao et al. 2021a) (**Figure 5**).

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**Figure 5.** The two main directions of lithium-ion battery cathode chemistry – higher voltage and higher specific capacity. Source: Modified from Wu et al. 2020.

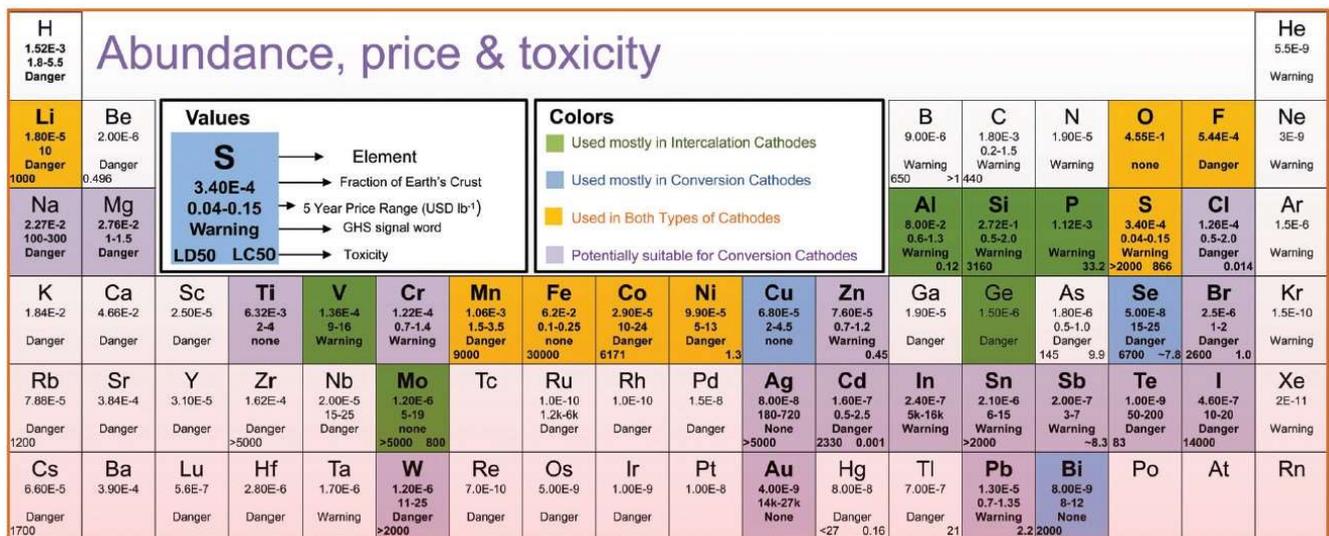
### 3.1.3 High voltage cathodes

Lithium Nickel Phosphate (LNP,  $\text{LiNiPO}_4$ ), Lithium Cobalt Phosphate (LCP,  $\text{LiCoPO}_4$ ) and Lithium Nickel Manganese Oxides (LNMO,  $\text{LiNiMnO}_4$ ) all offer potential voltages of almost 5 V versus 3.4 V for LFP and 3.8 V for NMC (**Table 1; Figure 4**). LNMO is the most likely to achieve commercialization first, however none of these cathode chemistries are currently close to commercialization, with current experimental cells showing only average specific energy capacity values and poor performance in other metrics such as thermal stability, cycle lifespan and durability (Wu et al. 2020). Lithium Manganese Iron Phosphate (LMFP,  $\text{LiMnFePO}_4$ ) meanwhile is a high voltage version of LFP (potential voltage 4.1 V), achieved through replacement of varying proportions of iron with similarly low-cost/high availability manganese (Li et al. 2002). Blended anodes with further metal additions are also being researched (Zhang et al. 2022). LMFP cathode chemistry offers up to 20% more specific energy capacity than LFP and pure/blended LMFP cells are likely to achieve commercial production in 2023 (PushEVs 2022).

### 3.1.4 High specific energy capacity cathodes

Higher specific energy capacity increases are being addressed in two ways – the use of metal halide cathodes, and the use of chalcogen cathodes (Wu & Yushin 2017; Wang et al. 2019c; Wu et al. 2020; **Figure 6**). Most of the currently commercially produced lithium-ion cathodes are intercalation cathodes, for which lithium ions are reversibly included within materials with layered structures during charging and discharging. In contrast, both metal halide and chalcogen cathode chemistry groups include mainly conversion cathodes, where materials react during charge and discharge to form new products (Yu et al. 2018). Such conversion cathodes allow the possibility of both higher potential voltages and specific energy capacities than current commercial intercalation cathodes, and these could potentially be applied to both lithium-ion and other potential rechargeable battery chemistries (Wang et al 2019c; Wang et al. 2021).

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**Figure 6.** Elements used in current intercalation and conversion cathodes of lithium-ion batteries, and potential future conversion cathodes. Source: Wu & Yushin 2017.

### 3.1.4.1 Metal halide cathodes

Of the metal halide cathodes, CuF<sub>2</sub> offers comparable potential voltage to the commercially available lithium oxide cathodes (3.55 V) and considerably higher specific energy capacity, more than double the lithium oxides. FeF<sub>3</sub> has lower potential voltage (2.74 V) but even higher specific energy capacity, especially gravimetric where it offers potentially greater than three times the energy density of the lithium oxides and four times that of LFP. The metal chlorides CuCl<sub>2</sub> and FeCl<sub>3</sub> offer similar voltage potentials, twice the gravimetric specific energy capacity of existing cathode chemistries and moderate increases in volumetric specific energy capacity (**Table 1**).

### 3.1.4.2 Chalcogen cathodes

The second research direction for increasing the specific energy capacity of lithium-ion batteries with new cathode chemistries is the use of chalcogen elements and lithium chalcogenides (Whittingham 1978; Wu & Yushin 2017). Sulfur offers lower theoretical voltage potential than oxygen, and both are below those of current commercial cathode chemistries. However, very high gravimetric specific capacities – around eight times those of commercial cathodes – are predicted for both when in elemental form, and two (sulfur) to three (oxygen) times higher volumetric values. The addition of lithium, as Li<sub>2</sub>S or Li<sub>2</sub>O<sub>2</sub>, reduces theoretical gravimetric values to around five to six times those of commercial cathodes, but has no effect on voltage potential or volumetric specific energy values and may be a viable strategy for working towards all-sulfur or all-oxygen cathodes (Wu et al. 2020) (**Table 1**).

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## 3.2 Anode

While numerous hypothetical anode materials have been proposed, a narrower range of materials has been investigated for the anode of lithium-ion batteries than for the cathode, and far less materials have made it to commercial production than for cathodes.

### 3.2.1 Past and present lithium-ion battery anode chemistries

Carbon in the form of graphite is currently the only widely used anode material in lithium-ion battery manufacture. Lithium titanate ( $\text{Li}_4\text{Ti}_5\text{O}_{12}$ , LTO) is also commercially available and although it offers similar volumetric specific energy capacities, higher voltage potential than graphite, lower gravimetric specific energy capacity, and the increased cost of the materials have all resulted in a general lack of adoption (Lu et al. 2018) (**Table 2**). It may however be that its working voltage against lithium of 1.55V (**Table 2**), which improves safety and charge speed, will promote its use in niche applications such as medical devices. Related materials such as niobium titanium oxide and niobium tungsten oxide are under development to retain such charge and safety benefits but boost energy capacity closer to that of graphite anodes (Grey & Hall 2020).

**Table 2** Properties of anode materials (modified from Wu et al. 2020)

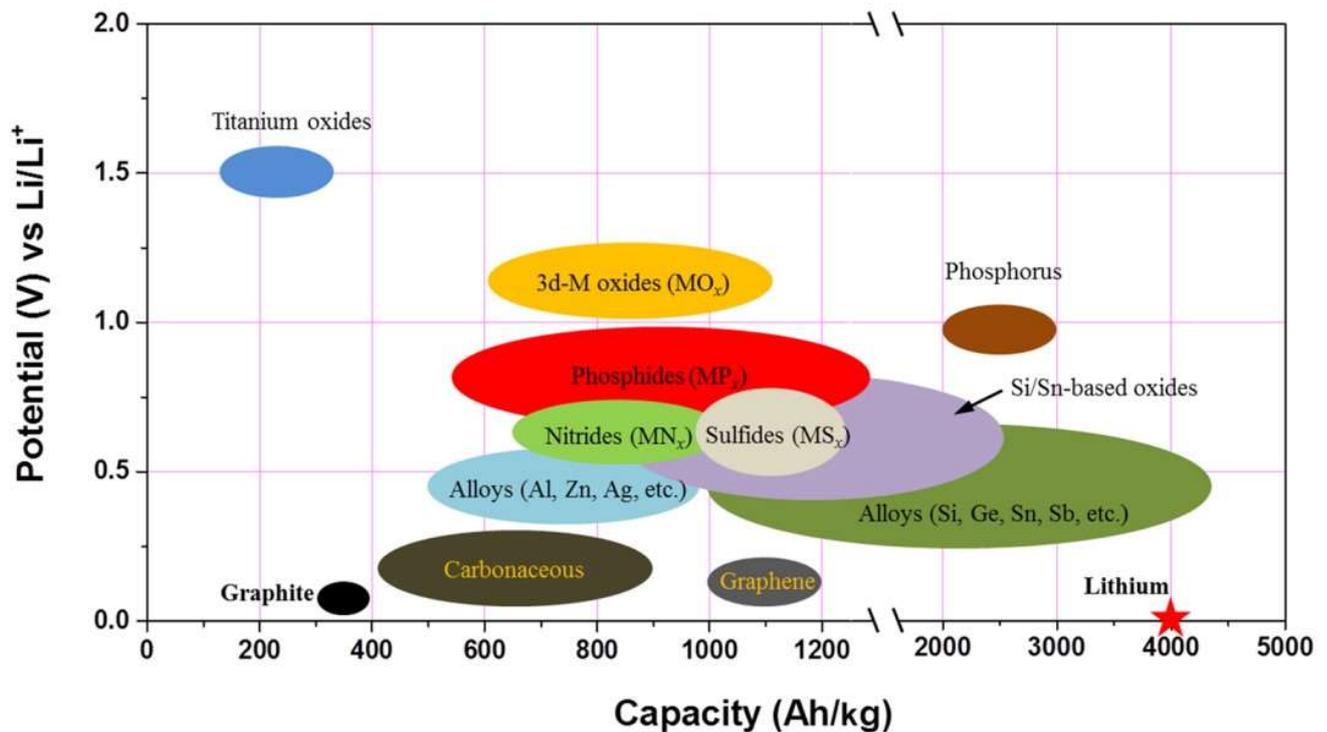
Active materials	Specific capacity $\text{mA h g}^{-1}/\text{mA h cm}^{-3}$	Potential (V vs. $\text{Li}^+/\text{Li}$ )
Currently commercially available		
Graphite	372/735	0.17
$\text{Li}_4\text{Ti}_5\text{O}_{12}$ , (LTO)	175/607	1.55
Future		
Li	3861/2062	0
Si	3579/2190	0.4
$\text{Fe}_2\text{O}_3$	1007/2741	1.2
Al	993/1386	0.38

### 3.2.2 Future lithium-ion battery anode chemistries

As with lithium-ion battery cathodes, future anode chemistries are targeted at increased specific energy capacity, but for anodes this needs to be accomplished while minimising the voltage potential. Many promising candidates exist, including earth-abundant metals such as zinc, aluminium, iron and magnesium, but by far the best two are silicon (and silicon oxides,  $\text{SiO}_x$ ) and lithium. Both have relatively low voltage potentials, with silicon slightly higher and lithium slightly lower than graphite

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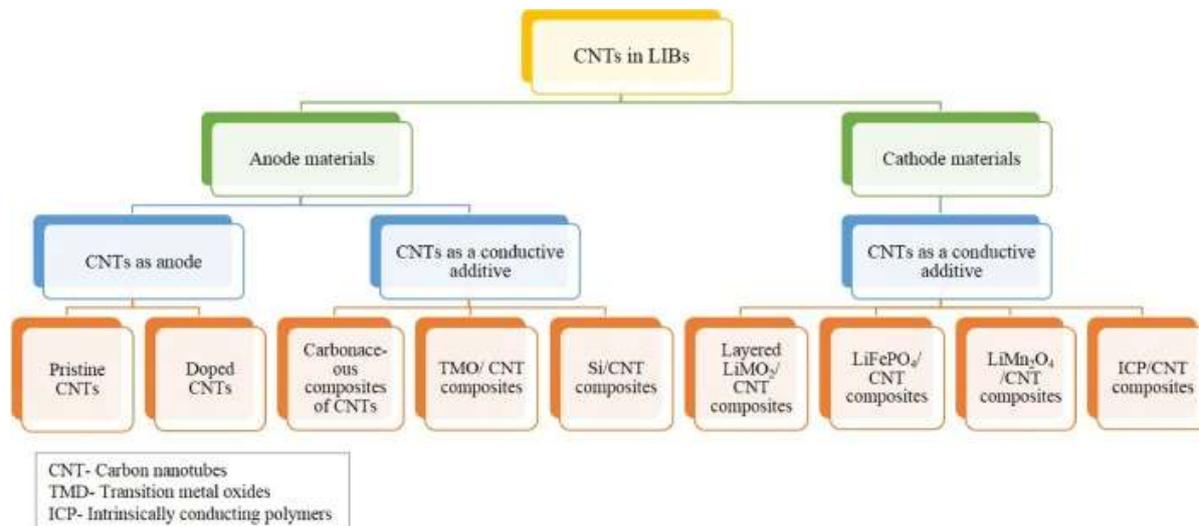
anodes. They also both have approximately four times higher volumetric and ten times higher gravimetric theoretical specific energy capacities than graphite anodes (Lu et al. 2018; Wu et al. 2020) (Table 2; Figure 7).



**Figure 7.** Specific gravimetric energy capacity against potential voltage for the main current and proposed lithium-ion battery anode chemistries. Source: Lu et al. 2018.

Silicon is often present in the anodes of existing modern commercial high capacity NCA and NMC cells in low quantities, around 2-10%, offering minor energy capacity increases (Grey & Hall 2020). Pure silicon anodes have already hit the market in low-volume, high-end applications e.g. satellites, and offer up to twice the final cell level gravimetric and volumetric specific energy capacities of currently commercially available graphite anode lithium-ion batteries (Electdrive.com 2022). These have cell level gravimetric density of just under twice current NMC and NCA batteries, and volumetric density of just over twice. Currently the cost of silicon production with these specifications is very high and the volumes very low – production of silicon nanowires forms the basis of the first available anodes of this type. The properties of the silicon and its nanowire structure both contribute to the potential for very fast charge times, another parameter of increasing importance to the makers of electric vehicles, especially as battery energy sizes grow with larger sized vehicles like long-haul lorries/trucks. In general, strategies for controlling the nanostructure of both carbon and silicon for use as the anode in lithium-ion batteries are being heavily researched (Su et al. 2014; Kumar et al. 2018; Figure 8).

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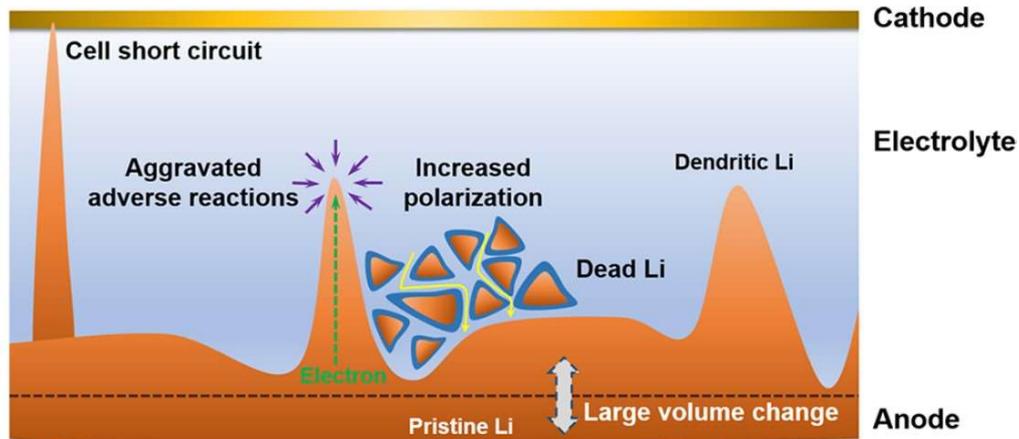


**Figure 8.** Methods for incorporating Carbon NanoTubes (CNT) into lithium-ion batteries, as anode material or conductive additives. Source: Kumar et al. 2018.

In parallel, a number of research projects and manufacturers are pursuing a graphite/silicon mixed anode (Chae et al. 2020) to introduce some of the benefits of silicon while minimizing some of the negatives such as large volumetric change on charge/discharge and unstable interfaces between the silicon and electrolyte material (Wu et al. 2020; Li et al. 2021). These also are commercially available, with e.g. silicon coated carbon nanoparticles used in wearables (Bellan 2021), and with a number of startups and manufacturers working with electric car producers (Griffith 2022). It is likely that many of the near-term improvements in lithium-ion battery specific energy capacities will come from changes in the anode material from pure graphite to carbon and/or silicon nanostructures. These will work with all lithium-ion battery cathode chemistries and, alongside benefits such as considerably faster safe charging times, will likely improve the energy capacity parameters between 25 and 100%. Such large increases benefit the lithium-ion battery ecosystem in several ways: the global kWh production capacity will increase by similar percentages, likely with lower percentage cost increases. This will enable the transition to full electrification to happen faster than with current battery technology, while reducing the amounts of other raw materials required, especially the cathode materials, by similarly high percentages (Turcheniuk et al. 2021).

Lithium metal anodes are probably the next-closest to market new anode chemistry for lithium-ion batteries. Because of their lower, zero voltage potential difference and slightly higher gravimetric/slightly lower volumetric potential specific energy capacities than silicon, intense research to overcome current safety issues – very large volume changes and the potential for short circuits especially – is ongoing (Cheng et al. 2017; **Figure 9**).

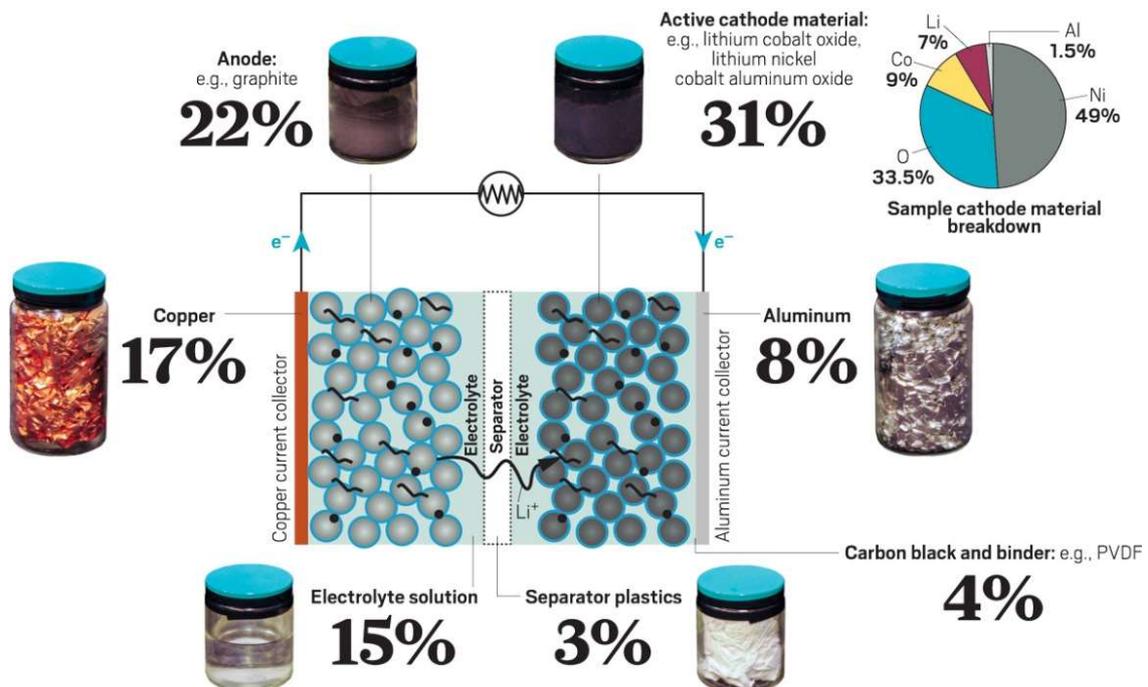
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**Figure 9.** Safety, reliability and efficiency issues to overcome for lithium metal anodes. Source: Cheng et al. 2017.

### 3.3 Other components

The main components of lithium-ion batteries in addition to the cathode and anode are copper as a current collector, aluminium as a current collector and for cylindrical cells as the outer casing, LiPF<sub>6</sub> salts dissolved in carbonate solvents as the electrolyte, polymer separators, carbon black as an additive, and polyvinylidene fluoride (PVDF) as a binder material (Zeng et al. 2014; Yamada et al. 2019; **Figure 10**).

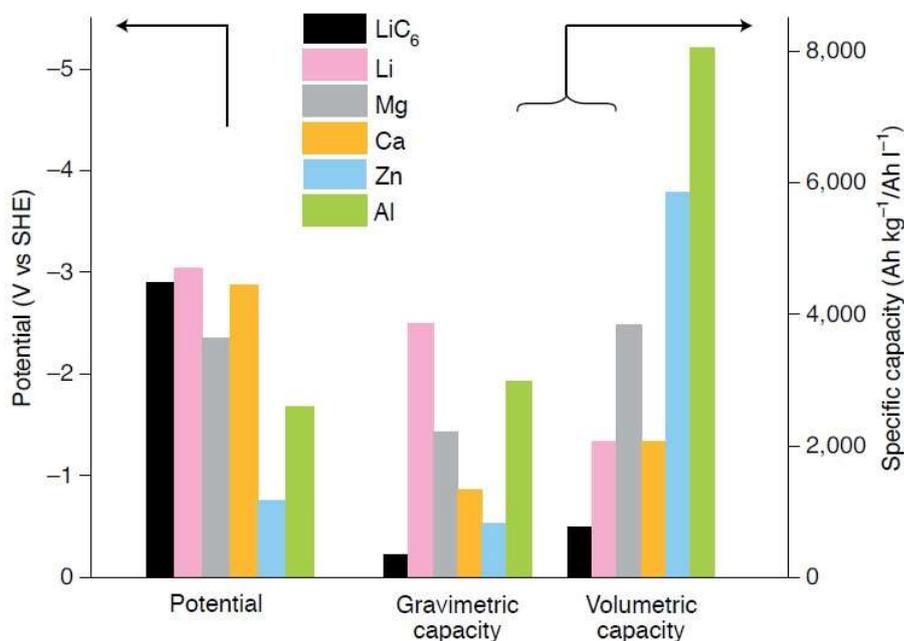


**Figure 10.** Breakdown of typical NCA cylindrical cell by weight of components. Source: Jacoby 2019.

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## 4 OTHER METAL-ION BATTERY CHEMISTRIES

While lithium-ion batteries are the most produced and used for energy storage systems and the electrification of transport, other metal-ion batteries chemistries exist. Those with moderate to high levels of research, development, and/or commercialization, include aluminium-ion, calcium-ion, magnesium-ion, sodium-ion and zinc-ion (Liang et al. 2020; **Figure 11**). Most of these metals are both more abundant and easier to process than lithium, potentially offering both cost and availability advantages over lithium-ion batteries once production is suitably scaled up. If rising demand and mineral availability constrained supply results in increasing prices for lithium-ion batteries, especially those containing critical metal oxides, contrary to decreasing price trends over the last decade or so, then the economic feasibility of other metal-ion rechargeable battery chemistries will occur at earlier stages of the production scaling curve.



**Figure 11.** Potential, gravimetric and volumetric capacity for lithiated graphite (LiC<sub>6</sub>), lithium, and the multi-valent metals aluminium, calcium, magnesium and zinc. Source: Liang et al 2020.

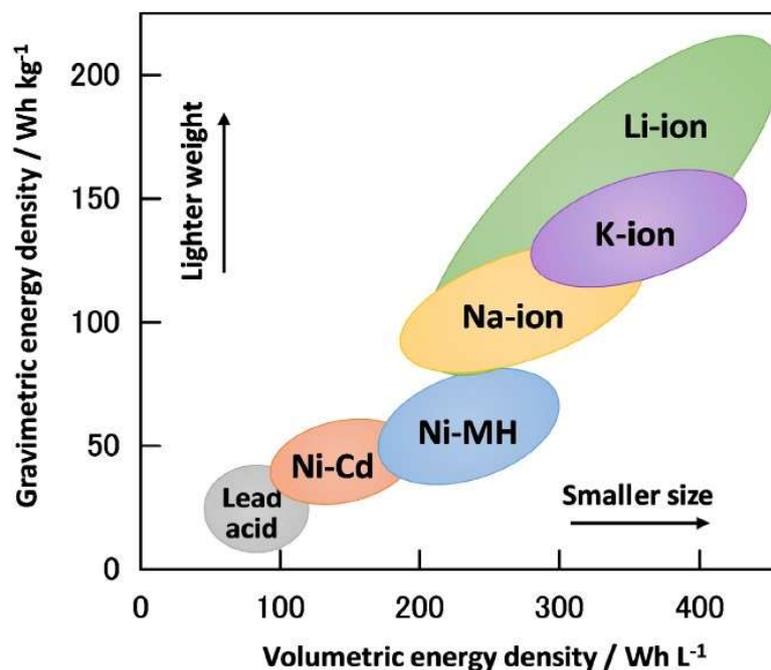
### 4.1 Sodium-ion

Sodium-ion batteries tend to have a similar structure to lithium-ion batteries, and the chemistry and electrochemistry are subtly different enough that although some materials can be common between them, different materials may also be required, principally for the cathode (Yabuuchi et al. 2014; Abraham 2020). One class of such materials used are the transition metal oxides familiar from lithium-ion batteries, such as iron, nickel, manganese and cobalt. Cathodes of NaCoO<sub>2</sub> and NaNiCoMnO<sub>2</sub> have been investigated, analogues of LCO and NMC lithium-ion battery cathodes, as well as some

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combinations unfamiliar from lithium-ion batteries such as  $\text{NaFeO}_2$ ,  $\text{NaNiO}_2$  and  $\text{NaNiCoFeO}_2$  (NCF). Similarly,  $\text{NaFePO}_4$  (NFP) is the equivalent of LFP, whereas other metal phosphates such as  $\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$  have no well-investigated lithium-ion equivalent. Iron cyanides such as Prussian blue,  $\text{Fe}_7(\text{CN})_{18}$  have also been researched in depth. Anodes are usually hard-carbon, though various metals and alloys, oxides, sulfides and phosphides have all been the subject of research (Li et al. 2018).

Sodium-ion batteries are already commercially produced, and some of the largest lithium-ion battery producers have roadmaps for sodium-ion battery development, improvement and production. The currently realized specific energy capacities of sodium-ion batteries are lower than those of lithium-ion, though higher than those for lead-acid, nickel-cadmium (NiCad) and nickel-metal hydride (NiMH) rechargeable batteries, the three technologies most widely used before the commercialization of lithium-ion batteries (Kubota et al. 2018; **Figure 12**). This indicates that, should they be widely produced, they will likely occupy a similar market position to LFP batteries and used for stationary energy storage or for low-range/low-cost electric vehicles. However, aspects of their safety such as lower potential for thermal runaway than lithium-ion batteries (Zhao et al. 2013) and a possible edge in recyclability (Hirsh et al. 2020), in addition to potential economic and material availability advantages (for instance, they can use aluminium instead of copper foil as current collectors at both anodes; Kubota et al. 2018), may lead to faster and/or greater adoption than would otherwise have been the case.



**Figure 12.** Energy density (volumetric and gravimetric) of existing and potential future battery chemistries, highlighting the position of sodium-ion overlapping the lower bounds of current lithium-ion battery chemistries. Source: Kubota et al. 2018.

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## 4.2 Zinc-ion

Zinc-ion rechargeable batteries are possibly the second most promising metal-ion alternatives to lithium-ion in the short term, behind sodium-ion batteries. However, they offer additional benefits that sodium-ion does not. In addition to zinc being an earth-abundant metal; zinc-ion batteries can use an aqueous electrolyte which dramatically reduces the safety risks versus the combustible electrolytes typically used in lithium-ion batteries; they can be manufactured using similar processes to lithium-ion batteries but with production steps not bound by the dry-air requirements of lithium; and they potentially have both higher cycle lifespans and, possibly, higher specific energy capacity values than lithium-ion batteries (Fang et al. 2018; Wang et al. 2019b).

Vanadium and manganese oxides ( $ZnV_2O_5$ ,  $MnO_2$ ), as well as Prussian blue  $Fe_7(CN)_{18}$  and related compounds have been proposed and used as cathode materials, while zinc metal is often used for the anode.

## 4.3 Calcium-ion, Aluminium-ion, Magnesium-ion

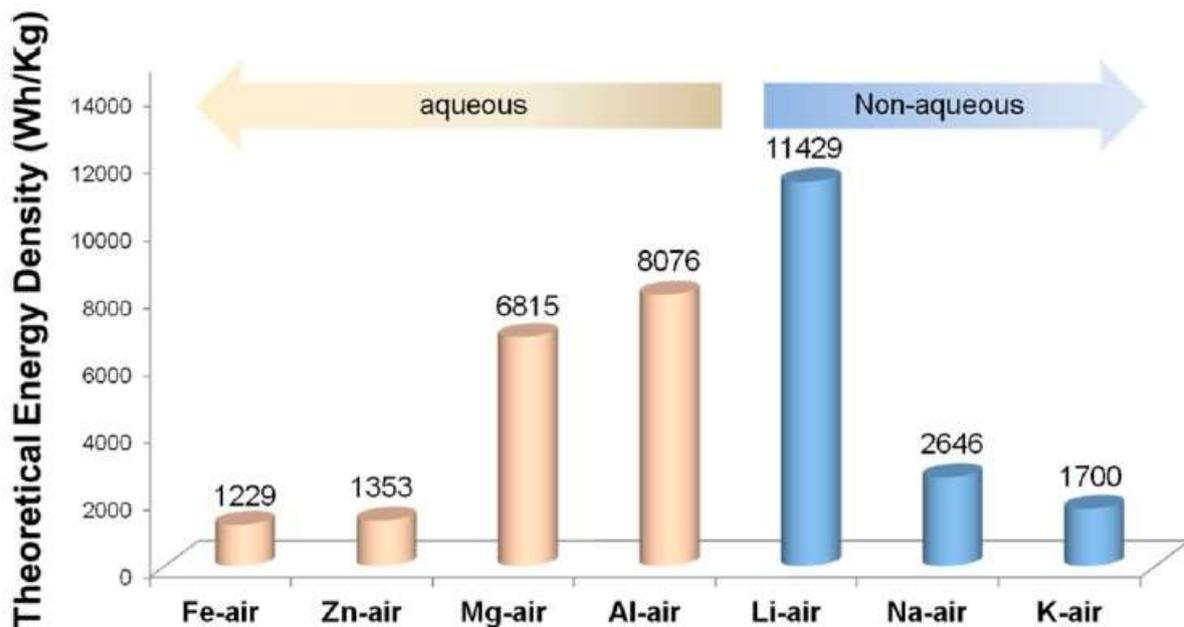
Research into calcium-ion, aluminium-ion and magnesium-ion rechargeable batteries lags behind that for lithium-, sodium- and zinc-ion batteries (Guo et al. 2020; You et al. 2020; Ji et al. 2021; Shen et al. 2021). Various advantages over other metal-ion batteries, including lithium-ion, may be apparent for each type. For instance, extremely rapid charging of aluminium-ion batteries with minimal effect on an already high lifetime cycle number may be possible, with a graphene cathode and aluminium anode (Shen et al. 2021). Predicting which of the many materials that have been suggested or researched for use as anodes and cathodes will end up being adopted if one of these battery chemistries reaches widespread commercial production is extremely difficult. Common themes are the possible use of transition metal oxides and sulfides as cathode materials and metal calcium, aluminium or magnesium as anodes.

## 5 METAL-AIR BATTERIES

Metal-air batteries, with metal anodes and oxygen containing air cathodes, have been in development, initially as primary, non-rechargeable batteries, for a long time (Li & Lu 2017). Rechargeable versions are a relatively recent research area. Their potential benefits are high to very high specific energy capacities (**Figure 13**) and potentially low costs – the anode can be an earth-abundant, non-critical and low-cost metal such as aluminium, iron or zinc (although lithium-air batteries offer the possibility of the highest energy storage), and the cathode is oxygen from the ambient air (Wang et al. 2019a). However, many problems with the technology remain to be overcome before metal-air batteries can be widely commercialized – the metal anode is liable to corrosion, deformation, hydrogen formation and dendritic formation leading to short circuits, while the cathode (air) side lacks efficient catalysts required to speed up the oxygen reactions, and both anode and cathode potentially form side reaction products that can block both the metal anode and air/oxygen diffusion at the cathode. Metal-air

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batteries can also be made as flow batteries (see next section) and flexible, small-form factor batteries (e.g. zinc-air, Lorca et al. 2020), but the latter are unable to much contribute to the challenges of transportation electrification and large-scale static energy storage (Wang et al. 2019a).



**Figure 13.** Aqueous and non-aqueous metal-air rechargeable batteries and their theoretical energy densities. Source: Li & Lu 2017

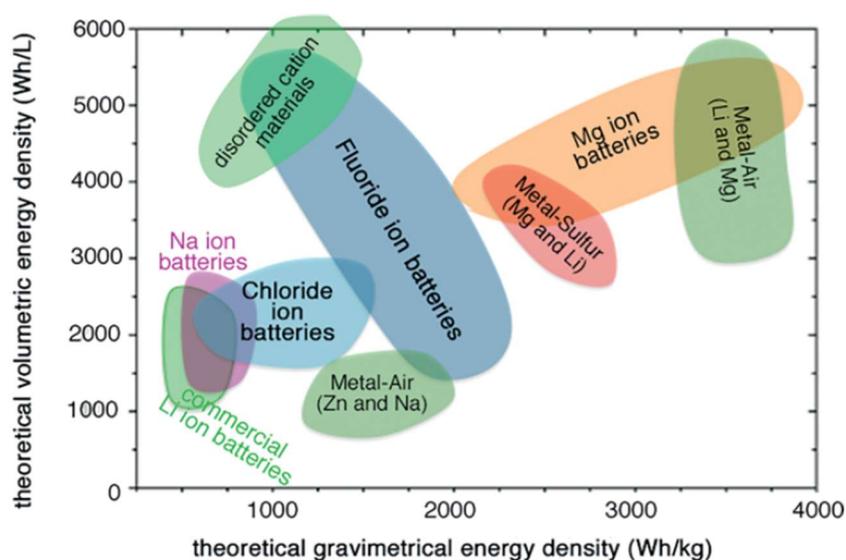
## 6 ANION BATTERIES

The above metal-ion batteries all involve the flow of positive cations from the cathode to anode and back during charge and discharge cycles. Another class of battery chemistries instead uses negative anions. These include the above-mentioned lead-acid batteries using  $\text{HSO}_4^-$  ions, nickel-cadmium (NICAD) and nickel-metal hydride (NIMH) batteries using  $\text{OH}^-$ , fluoride-ion ( $\text{F}^-$ ) batteries and chloride-ion ( $\text{Cl}^-$ ) batteries. All have aqueous electrolyte and so share quite low fire risks. NICAD and NIMH chemistries were the first widely available small form factor rechargeable batteries for portable electronics, and are intermediate between lead-acid and lithium-ion batteries in energy density, but were replaced by lithium-ion in the main due to its higher energy capacities (**Figure 12**). The high levels of toxicity of cadmium in NICAD batteries also lead to them being mostly replaced, with e.g. the EU requiring NICADs be replaced with NiMH, and considerable research has gone into the recovery of cadmium from spent NICAD batteries (Assefi et al. 2020). NiMH batteries were used in early hybrid cars before lithium-ion use became commonplace. NICAD batteries use nickel oxide hydroxide ( $\text{NiOOH}$ ) cathodes and cadmium anodes, NIMH batteries use the same nickel oxide hydroxide cathode and the anode a complex mix of metals such as titanium, vanadium, nickel, chromium, manganese, and in some versions rare-earth metals like neodymium, lanthanum, cerium etc (Fetcenko et al. 2007).

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## 6.1 Chloride-ion batteries

Because of the wide availability of chloride materials, it has been suggested that they may make a good future solution to supply deficits of critical metals in other battery chemistries. Chloride-ion rechargeable batteries are a relatively recent development, with little in the way of a route to commercialization yet. Although the theoretical energy capacity for chloride-ion batteries is high (**Figure 14**), it has been said that commercial products likely won't reach the energy density or voltage potentials of lithium-ion batteries (Gschwind et al. 2017). Because of their relative newness, the range of theoretical materials under current consideration for chloride-ion batteries is vast. In general, those with the highest theoretical capacities include carbon tetrachloride ( $\text{CCl}_4$ ) and the highly toxic/reactive selenium tetrachloride ( $\text{SeCl}_4$ ) as cathodes, while  $\text{AlCl}_3$  is the most stable of the relatively high-capacity cathodes (Gschwind et al. 2017). For anodes, a range of metals including Ca, Na, Mg, Al and Ti offer good theoretical properties. In practice, working batteries have been made in the lab with cathodes of  $\text{FeOCl}$ ,  $\text{VOCl}$ ,  $\text{BiCl}_3$ ,  $\text{VCl}_3$  and  $\text{BiOCl}$ , paired with Li Zn or Mg anodes.



**Figure 14.** Theoretical gravimetric and volumetric energy density for chloride-ion batteries relative to other rechargeable battery chemistries. Source: Gschwind et al. 2017.

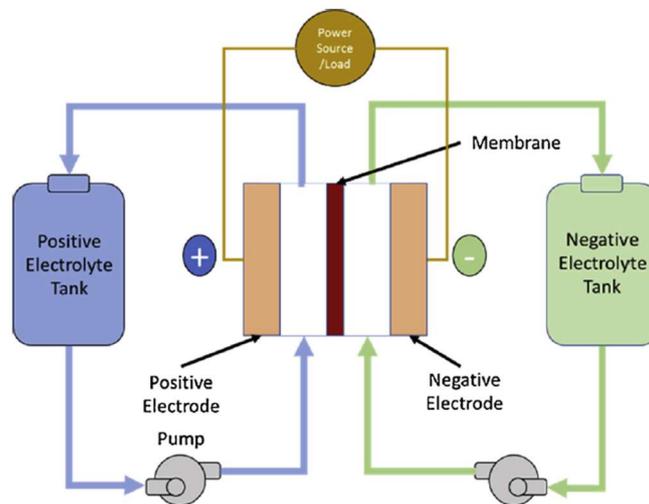
## 6.2 Fluoride-ion batteries

Fluoride-ion batteries are at an even earlier state of development than chloride-ion ones, and have similar production problems relating especially to a lack of suitable fluoride transporting electrolyte material to date (Karkera et al. 2021). They have higher theoretical energy density than chloride-ion batteries (**Figure 14**) and again the range of theoretical materials under consideration for fluoride-ion batteries is vast, with cathodes like  $\text{CuF}_2$ ,  $\text{PbF}_3$  and  $\text{BiF}_3$ , and anodes Li, Na, Mg or Ce some of the most likely chemistries to be used.

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## 7 VANADIUM REDOX FLOW BATTERIES

Redox flow batteries are a class of battery suited to static energy storage systems but not transport electrification due to their low energy densities. They use large tanks of electrolyte to store and release charge, with mechanical pumps cycling the electrolyte past a membrane surrounded by the electrodes, and the ions flow across the membrane to drive charge/discharge processes (**Figure 15**). Redox flow batteries can potentially fully charge and discharge with no negative effects on cycle life, leading to - in theory - batteries with no cycle life limit (Lourenssen et al. 2019). They have short response times, making them suitable for use in power leveling of intermittent renewable electricity production, and relatively low capital and running costs relative to other large scale static energy storage systems. Such batteries also mainly use non-flammable electrolytes, which results in them offering potentially better safety than lithium-ion batteries.



**Figure 15.** Working diagram for a generalized redox flow battery. Source: Lourenssen et al. 2019.

Of those redox flow battery systems investigated to date, vanadium flow systems are the most advanced, with large-scale commercial systems already in existence. The largest to date is an 800MWh system in China (Service 2018). Vanadium redox flow batteries have some advantages over other redox flow chemistry batteries. These include lower levels of gas production during fast charge, the possibility of electrolyte recycling, and decent efficiency levels. Disadvantages include the requirement for temperature regulation to between 10 °C and 40 °C to minimize vanadium thermal precipitation, and what gas production there is at the electrode leads to electrode damage and results in charge depletion and lowered efficiency (Lourenssen et al. 2019).

In terms of material requirements, the majority of the system is comprised of two large tanks of electrolyte solution plus the pipes and pumping equipment needed to keep the electrolyte flowing across the ion exchange membrane. The electrolyte is typically  $V_2O_5$  or  $VOSO_4$  in sulfuric acid ( $H_2SO_4$ ). The electrodes, which need to be resistant to sulfuric acid corrosion, are usually carbon or graphite, and the ion exchange membrane is polymer based.

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## 8 OTHER REDOX FLOW BATTERY CHEMISTRIES

Because vanadium is a critical metal and potentially subject to limited supply and rapid price increases, other redox flow batteries have been proposed and researched. Zinc-bromine flow batteries or hybrid batteries are the other main flow batteries so far to be taken as far as industrialization (Sánchez-Díez et al. 2021). The electrolyte is a zinc bromide aqueous solution which is used in both tanks, but while the bromine is dissolved at all times, the zinc is solid when the battery is charged and is dissolved when it is discharged. The solid zinc plates the negative electrode, giving the battery its hybrid nature. Together, these properties give the batteries the disadvantage that dendrites leading to blockage of the electrolyte flow can form, and without expensive additives, toxic bromine vapour emissions can occur.

Other, less well studied and less produced redox flow batteries include; vanadium-oxygen, which by replacing one electrode with air, reduces the vanadium amount required, increases the energy density, and reduces vanadium precipitation risk at high temperature; vanadium bromine, which allows higher vanadium concentration than all-vanadium systems and so increases energy density, and allows for both lower and higher temperature operation; hydrogen-bromine, which has been commercially implemented on a small scale and allows further energy density increases but has the toxicity issues of bromine plus the flammability of hydrogen to contend with; aqueous organic redox flow batteries, which replace the electrolyte with redox active organic molecules such as carbon, hydrogen, oxygen, nitrogen or sulfur and can allow higher voltage potential and higher solubility increasing energy capacity, though are often currently employed only in the anode side of the system as anolyte replacement; for hybrid flow-non flow batteries, iron and copper have been suggested as alternatives to zinc; and an emerging class of metal-air flow batteries has been researched using zinc, aluminium and lithium as metal anodes (Sánchez-Díez et al. 2021).

Hybrid lithium-ion/vanadium redox flow static energy storage systems have also been implemented to complement the positive features and characteristics of each battery type and minimize the negatives (EnergySuperhubOxford 2021).

## 9 SOLID-STATE BATTERIES

Solid-state batteries are less of a single chemistry or family of chemistries, and more of a battery production method. They use solid instead of liquid electrolytes, and this solid electrolyte often also works as the separator between the two halves of the cell. Solid-state batteries are not limited to lithium-ion battery chemistries, and have also been proposed for other chemistries including other metal-ion chemistry batteries and redox flow batteries (Zhao et al. 2018; Zhao et al. 2020; Wang & Chai 2021).

However, solid-state batteries may be the format that allows many of the potential technical advances currently being researched for lithium-ion batteries to be realized, rather than 'traditional', liquid electrolyte and polymer separator lithium-ion batteries (Manthiram et al. 2017). The solid electrolyte working as a separator can form a better barrier than conventional separators, stopping the growth of dendrites between cell halves and reducing the risk of short-circuits. By doing so, the solid separator

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potentially allows the use of metal anodes including lithium without the safety issues that have so far stopped their commercial use (Chen et al. 2019). The lack of flammable liquid electrolytes also increases safety and further contributes to the large potential increases in volumetric energy density. It has also been reported that a solid separator better enables the use of carbon-free silicon anodes (Tan et al. 2021).

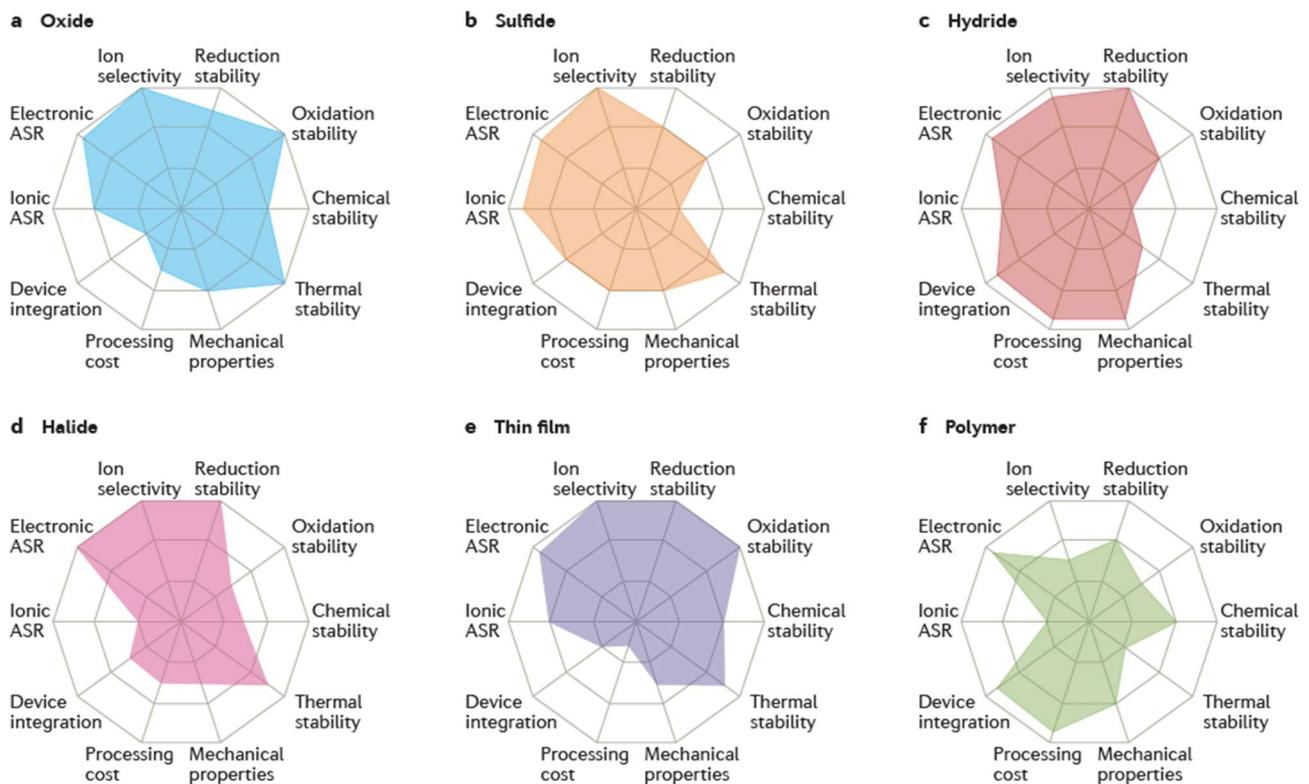
Similarly, solid-state batteries may allow some of the above-mentioned advances in cathode chemistry for lithium-ion batteries to be realized. The use of solid-state batteries with a lithium metal anode and sulfur cathode overcomes two of the problems associated with the use of sulfur as a cathode material in conventional lithium-ion batteries – dendritic lithium growth leading to short circuiting, and the dissolution of sulfur in liquid electrolyte which leads to poor efficiency and low cycle counts (Lei et al. 2018). Likewise, lithium-oxygen (lithium-air) batteries with oxygen cathodes may only be possible with the use of solid-state electrolytes (Liu et al. 2018a).

A wide variety of materials has been proposed for the manufacture of the solid electrolyte itself. These include (Manthiram et al. 2017; **Figure 16**):

1. Oxides: perovskite ( $\text{LiLaTiO}_3$ ), garnet ( $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ ), sodium superionic conductor NASICON ( $\text{LiTi}_2(\text{PO}_4)_3$ ), lithium superionic conductor LISICON  $\text{Li}_{14}\text{Zn}(\text{GeO}_4)_4$
2. Sulfides:  $\text{Li}_2\text{S}-\text{P}_2\text{S}_5$ ,  $\text{Li}_2\text{S}-\text{P}_2\text{S}_5-\text{MS}_x$
3. Hydrides:  $\text{LiBH}_4$ ,  $\text{LiBH}_4-\text{LiX}$  ( $X=\text{Cl, Br or I}$ ),  $\text{LiBH}_4-\text{LiNH}_2$ ,  $\text{LiNH}_2$ ,  $\text{Li}_3\text{AlH}_6$ ,  $\text{Li}_2\text{NH}$
4. Halides:  $\text{LiI}$ , spinel  $\text{Li}_2\text{ZnI}_4$  and anti-perovskite  $\text{Li}_3\text{OC}$
5. Borates and phosphates:  $\text{Li}_2\text{B}_4\text{O}_7$ ,  $\text{Li}_3\text{PO}_4$  and  $\text{Li}_2\text{O}-\text{B}_2\text{O}_3-\text{P}_2\text{O}_5$
6. Thin film: LiPON
7. Polyethylene oxide (PEO) polymer

Hybrid or semi-solid-state batteries are also being researched, in which one side of the battery and/or the separator is replaced with solid-state material, but the other retains a liquid or gel electrolyte (Lei et al. 2018; Liu et al. 2018b). This may be one route for allowing developments such as lithium metal cathodes to be more rapidly brought to market for lithium-ion batteries while otherwise using existing materials and production techniques.

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**Figure 16.** Radar plots of the performance of six different solid electrolyte materials; greater distance from center = better performance. ASR = area-specific resistance. Source: Manthiram et al. 2017.

## 10 PREDICTIONS

Predicting the future of rechargeable battery production and consumption, even over the relatively short-term, is difficult. Most market analyses from even just a couple of years ago predicted, based on prevailing trends, that LFP cathodes for lithium-ion batteries would slowly decline in production percentages compared with higher energy chemistries such as NMC (**Figure 3**; IHS Markit 2021). However, the combination of material availability and prices which affect critical element metals like nickel and cobalt, and the increasing demands for batteries in transport electrification and static energy storage, have led to the reversal of this trend and LFP likely becoming the most-produced chemistry in the very near future (NDRC 2022). This shows that aspects of economics and raw material availability are already drastically affecting the rechargeable battery market. At a broader scale, it is however clear that lithium-ion batteries will overtake lead-acid batteries to become the dominant technology in the very near future if they have not already, and that it will take a considerable amount of research, expenditure, and time for emerging technologies to equal or beat production volumes of current cathode and anode chemistry lithium-ion batteries. This is especially true given the planned and anticipated ramping increase in lithium-ion battery production volumes (currently a 25 times volume increase to >5TWh is predicted from 2020-2030, Benchmark Mineral Intelligence 2022).

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Extrapolating from such trends and taking into account the inertia of scaling up new chemistries we estimate that over the next ten years, by 2032, the following will occur in the rechargeable battery market:

- Total annual production capacity for rechargeable batteries will reach 7.5TWh or greater
- LFP/LMFP/LFP blended lithium-ion batteries will account for around half to two-thirds of this, roughly 4–5TWh
- Each of NCA, LCO, sodium-ion, and lead-acid chemistry batteries, plus redox flow and solid-state battery types (of any chemistry) will take between 2-10% of the total market
- NMC lithium-ion batteries will take most of the remaining production volume, between approximately 20% and 40%

As can be seen, this prediction is quite conservative in terms of the market share prospects for new entries into the rechargeable battery market – each of the chemistries listed in the prediction above is currently already in commercial production, even if at small scale, and the current lithium-ion chemistries are expected to remain dominant. Technological developments such as lithium metal anodes, with or without the transition to solid-state or partial solid-state batteries, can still use the same NMC and/or LFP cathodes and are most likely to happen for existing lithium-ion battery formats and production methods. The time before some or all of these technologies becomes economically competitive with current lithium-ion battery production – which will have had an additional ten years of optimization and cost benefits from massive scaling up – is also likely to be outside of this ten-year prediction timeline (Berdichevsky & Yushin 2020; Benchmark Mineral Intelligence 2021; Turcheniuk et al. 2021). Similarly, scaling of production volumes of these or other new technologies is likely to happen more slowly than the extremely rapid ramping up of lithium-ion battery manufacturing of existing commercially produced chemistries that is currently underway. Two main expected exceptions to this are 1) the use of nano-carbon and silicon, or composites including these, as anodes. The adoption of these at scale is likely to happen within this ten-year timeframe and will contribute in part to the predicted production capacity increases – with these advances, each cell produced will contain more energy, allowing greater capacity output for the same number of cells produced (Berdichevsky & Yushin 2020). Similarly, 2) a partial or wholesale switch from lithium-ion LFP cathodes to higher voltage potential LMFP or LFP blended cathodes within the ten-year timeframe seems feasible and would further contribute to production capacity increases. A third (though we consider it less likely) possibility is the commercial development of high voltage cathode chemistry lithium-ion batteries such as LNMO, which would potentially achieve similar results due to its similar energy densities to current NCA and NMC batteries and higher voltage potential (IEA 2021b).

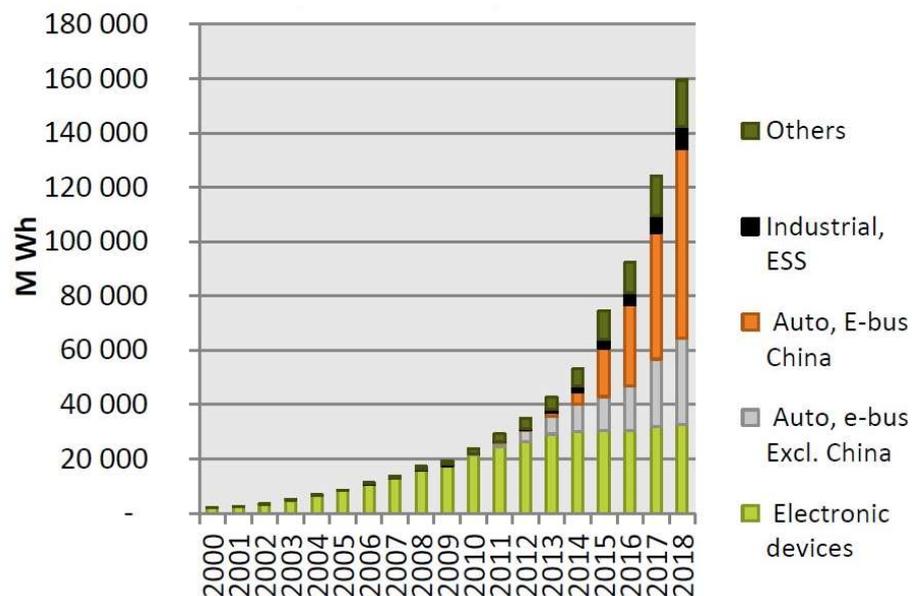
However, in terms of critical raw material requirements, this prediction may also be quite radical, with a moderately varied ecosystem of eight or nine rechargeable battery chemistries or types being produced in significant numbers (as even 2% of 7.5TWh is 150GWh, which is roughly the total global lithium-ion battery production from as recently as 2018; Avicenne Energy 2019; **Figure 17**). In particular, it implies relatively low proportions of total annual battery production in 2032 will be reliant on critical minerals or metals such as nickel and cobalt (Olivetti et al. 2017; Turcheniuk et al. 2021; Zeng et al. 2022), other than lithium and vanadium. Vanadium will be required in large absolute but relatively

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small proportional amounts compared with the entire battery production volume. The elephant in the room is lithium (Greim et al. 2020), which is predicted to be required for between 70% and 90% of all rechargeable batteries produced in 2032 under this scenario. Whether these demands are achievable relative to current critical battery mineral reserves, stockpiles, and current and planned future production will form the basis of a further report to be compiled for this Work Package WP1.5 ('Raw materials for alternative battery chemistries') of the Business Finland funded project BATCircle2.0. If they are not achievable, and e.g. lithium becomes the limiting factor due to price and/or lack of availability in sufficient amounts (Turcheniuk et al. 2021), then it becomes easy to foresee a much more rapid transition to alternative battery chemistries such as sodium-ion and redox flow in order to meet estimated demand production volumes.

In the longer run, looking at the less than 20 years from 2032 to 2050 and the net zero carbon goals set for that date (e.g. EU 2020) it becomes increasingly difficult to predict the direction of rechargeable battery development and production. Somewhat counterintuitively, the low energy densities of LFP chemistry lithium-ion batteries, and sodium ion batteries, may count against them, since cost/kWh will decrease less quickly than e.g. NCA, NMC, sulfur and air cathodes even when all are paired with combinations of silicon or metal anodes and in solid-state batteries (Turcheniuk et al. 2021). Most of the so-far not commercially made technologies should have reached large-scale production, or the possibility of it, during this time period. The turnover point of cost effectiveness versus performance of these other battery chemistries relative to the predominant chemistries of the time will likely determine which become the future widely used batteries. The availability of the raw materials required will also have considerable influence. This may be partially balanced against the increases in energy density associated with each of these technological developments as they have the potential to reduce relative (but not absolute) raw material requirements quite drastically, since doubling the energy density for the same amount of raw materials halves the total raw material demand for a given level of battery production. Recycling of the generations of lithium-ion batteries produced before 2050 will also provide access to another stream of raw materials without the requirement for more prospecting and mining (Ziemann et al 2018; Mayyas et al. 2019), though the degree to which this source will alleviate raw material demands is debated, especially as recycling will lag at least 10 years behind battery demand until the currently exponentially increasing demand and production amounts level off.

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**Figure 17.** Worldwide lithium-ion battery sales, 2000-2018, broken down by usage. ESS = Energy storage solution. Source: Avicenne Energy 2019.

## 11 CONCLUSIONS

A vast range of alternatives to the widely used lithium-ion battery chemistries exists. These range from commercially available and produced on a modest industrial scale through experimental production to theoretical only. Many variations on each main chemistry type exist, and it should be possible to choose future batteries on the basis of parameters like economic cost of materials, earth-abundance, environmental friendliness i.e. lack of toxicity, and recyclability. This will likely require some compromise in terms of other, performance-oriented parameters such as specific energy capacity, charge rate, cycle life etc. for each main chemistry type, so some optimization and compromise will be required between competing requirements. Alternatively, acceptable levels could be set for one or both sets of these economic/environmental versus performance parameters by producers, consumers, or legislators, possibly by usage class. This may already be happening to a degree with the accelerating production of LFP cathode lithium ion-batteries to rapidly become the majority produced lithium-ion battery type, and so the most-produced rechargeable battery type overall. If we are to achieve the rapid transition to an electrified world with transportation partially or fully electrified, and large-scale battery energy storage used to balance grids and provide backup for predominantly intermittent clean electric generation from solar and wind sources, careful balancing of these economic/environmental and performance battery parameter sets will be required. This could be achieved by considering battery production requirements from a mineral availability perspective, by designing all steps of the battery production, use and recycling chain with the raw materials firmly in mind (Neumann et al. 2022).

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