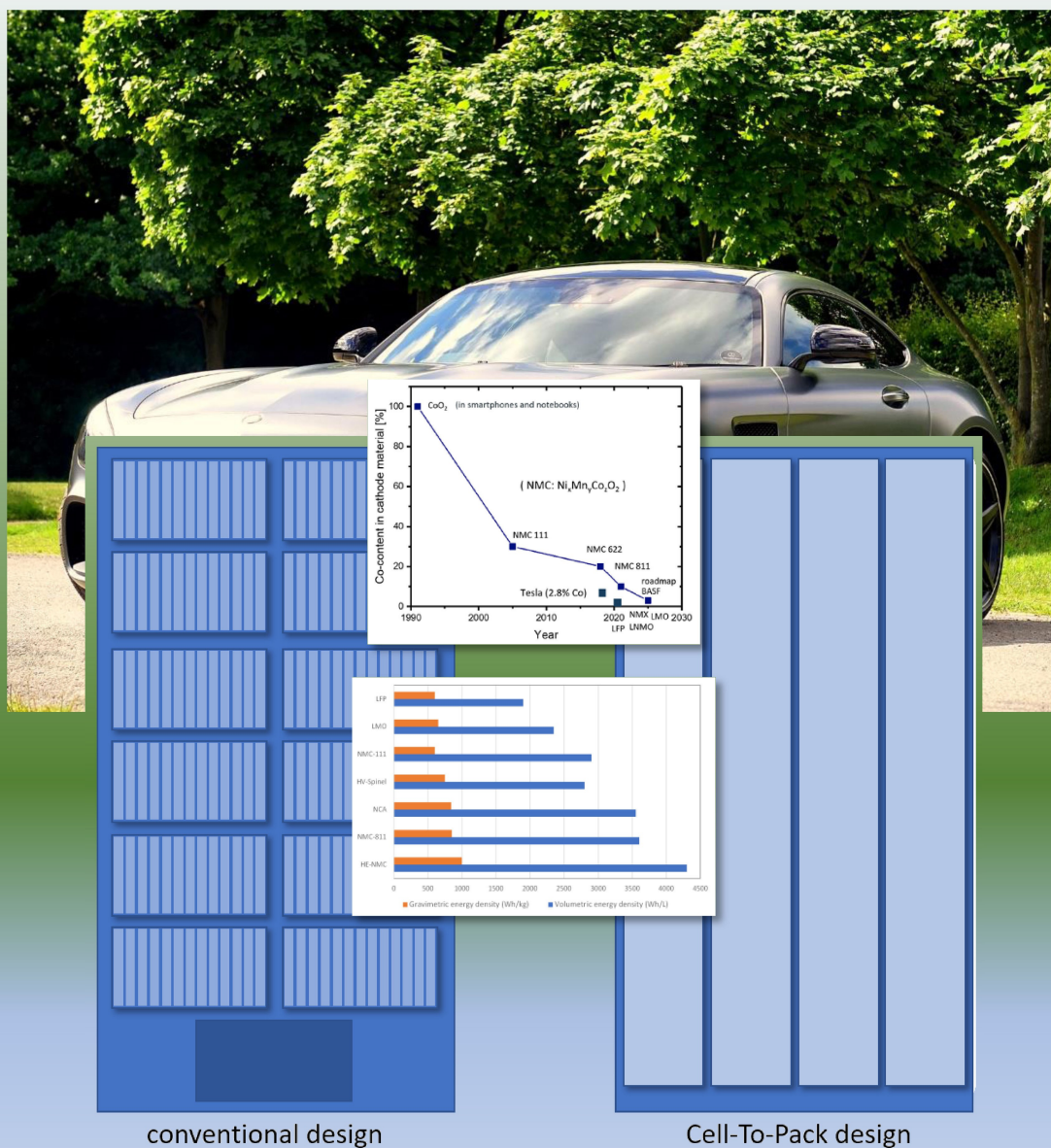


Recent Research and Progress in Batteries for Electric Vehicles

Maximilian Fichtner^{*[a, b]}



The developments in the field of e-mobility currently exceed all previous goals and expectations, and the speed of development is rapid. The battery costs dropped by 98% in the last three decades and the storage capacity increased by a factor of three to four in the same period. The recent strong progress in the development of lithium-ion batteries (LIB) can be associated to both the progress in the engineering of the battery pack, and the progress of active materials for the cathode. From the system perspective, only a fraction of the overall improvement is due to better chemistries. Even larger contributions are

expected from new cell-to-pack and the cell-to-chassis designs. The new designs provide more space for the active material so that also less energetic, but more sustainable, safer and cheaper materials can be (re)considered, such as LiFePO_4 which encounters a renaissance at the moment. The sodium ion battery is currently emerging as a potential alternative to the LIB. Li-air and Li-S batteries are not ready for application in cars, yet. A potential future candidate is the solid-state battery, which shall benefit from the use of a safe Li metal anode, delivering higher capacities and rate capabilities.

1. Introduction

Nowadays, we are surrounded by applications almost exclusively using lithium-ion batteries, or LIB for short. Over the years, several reasons have emerged that have pushed nickel-cadmium batteries already into niches, nickel-metal hydride batteries might follow. Apparently, LIB have been regarded as “better” for many applications. In general, such good or “better” batteries should store as much energy as possible in a small space, with low weight, they should be inexpensive and durable, they should consist of non-toxic components and be based on sustainably available raw materials, and they should be charged and discharged safely and quickly.

The triumphant advance of the LIB is mainly due to the first three points. In fact, since SONY launched the LIB in 1991, the storage capacity, i.e., the amount of energy contained in a lithium-ion battery, has quadrupled. At the same time, the price of battery cells fell by around a factor of 16, and it continues to fall, by around 10 to 15 percent per year. The first battery cells are meanwhile being offered for less than 100 USD per kilowatt hour.^[1] Until now, this was considered a magic limit, because below this value, battery-powered vehicles can be cheaper than comparable ones with combustion engine. In their 2017 study, the McKinsey agency did not forecast this until 2030, which shows the current momentum in this area.^[2] Likewise, the OPEC reported in 2015 that 4.7 Mio. electric cars could be expected in 2040.^[3] However, this number was reached as early as 2021, according to various sources.^[4]

The following article will give a brief overview on some of the major developments and trends in the first 20 years after commercialization of the LIB, and the actual routes will be addressed for further development of the cell chemistry. It is shown that considerable progress has been made with new cell

designs, which already had a major influence on the choice of cell chemistries so that a certain “twilight of materials” can be noticed. This fruitful interplay of engineering and chemistry already impacts the future performance, safety, cost, durability, and sustainability of Li based batteries.

2. The First 20 Years after Commercialization

After the first LIB was commercialized by SONY in 1991, with capacities of ca. 80 Wh kg^{-1} and 200 Wh L^{-1} , the cell chemistry was optimized in several steps. While the first cells were based on LiCoO_2 cathode and a petroleum coke anode, the addition of EC as co-solvent in 1991 allowed a protection of the graphite anode and higher operation voltages, which raised the energy density to 400 Wh L^{-1} , at a voltage of 4.2 V.^[5,6] Soon after, a new electrolyte formulation from Guyomard and Tarascon was introduced in 1993^[7] which consisted of LiPF_6 in an EC/DMC mixture. This electrolyte enabled a considerably increased energy density of 250 Wh kg^{-1} and 600 Wh L^{-1} and is still the most widely used today. Apart from additives for stabilization of the performance, the electrolyte and the graphite anode have remained more or less the same. At the cathode, however, there was always strong development going on.

The Co-oxide based cathode in its original form offers a superior volumetric energy density of 600 Wh L^{-1} , which is still one of the best choices when it comes to building very compact devices, e.g., smartphones and notebooks. For larger applications, however, also other factors come into play and it became soon clear that the use of cobalt entails serious disadvantages. The original cathode was critically examined, mostly because Co is a raw material which is expensive and toxic, and because it bears a certain risk potential. As a result, the chemistry of Co oxide has been rated as not suitable for automotive applications owing to its structural instability in the over-delithiated state. Moreover, at elevated temperatures around 200°C , oxygen is released which can oxidize combustible parts in the battery including the organic electrolyte. This reaction is strongly exothermic, may become self-sustained and leads to thermal runaway of the battery, fires, or even explosions.^[8]

In the search for more viable options, several strategies have been followed since then to reduce the Co content in battery materials. One of the most successful attempts is the

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substitution of the cobalt by nickel and manganese in the so-called nickel manganese cobalt oxide (NMC). The increasing degree of substitution has led to a continuous decline of the Co content in automotive applications, as is depicted in Figure 1.

Another material is NCA, where Co has been partially substituted by Ni and Al. While the first automotive battery cells based on NCA contained 12% Co, Panasonic lowered this fraction in the more recent models down to 2.8% in 2018. Overall, the Co content has been greatly reduced, the cell density of lithium-ion batteries has almost tripled in the last ten years and, according to BloombergNEF, costs have fallen by almost 90%.^[10]

3. Routes in the Actual Battery Development

The technical progress in the 2010s allowed to build systems with higher capacities and higher rate capabilities. However, the batteries still have not reached all the goals which have to be met to be ultimately competitive to combustion engines and fuel cell drivetrains. There are still the goals of further reducing weight, enabling a longer range, charging faster, reducing the risk of incidents and building batteries based on more sustainable element compositions.

Hence, a series of strategies has been followed to improve both cell chemistry and cell design. The further development of the cell chemistries addresses different materials chemistries and storage principles, whereby the developments show very different degrees of maturity. The most prominent development routes for the cell chemistry are either on Li-based batteries or on the so-called post-lithium systems, i.e. batteries, which do not rely on the shuttle of Li ions but on the shuttle of Na, Mg, Ca, Zn, Al, or other ions. Overarching goals in all of these systems is to both increase the storage capacity, the cell voltage and the durability. An overview on current routes together with a selection of respective research topics is given in Figure 2. The "Post-Li Batteries" in this Figure also include conversion type systems.

As mentioned above, the research had been focused mainly on the development of better and more sustainable and safe cathodes in recent years. These efforts led to a series of commercialized and candidate materials which are available meanwhile. An overview with a collection of current systems, together with their energy densities on a materials basis is given in Figure 3. Not all of the listed materials have reached a

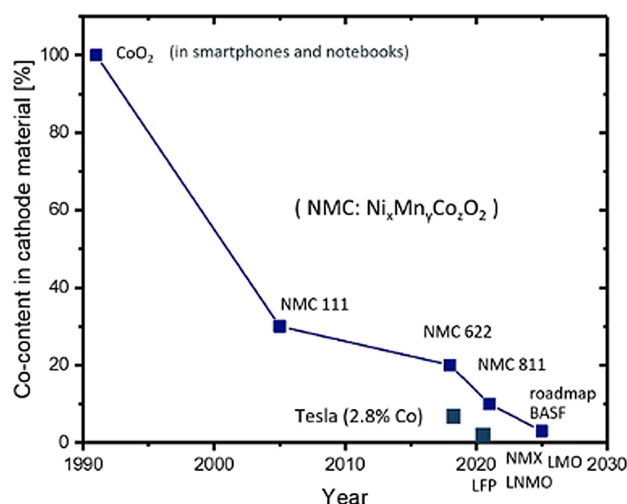


Figure 1. Co content in cathode materials for traction batteries over the years. The points have been set around the market introduction of the applications. Current materials which contain 0% Co are LFP (Li-iron phosphate), LMO (Mn spinel), LNMO, NMX^[9] (Ni–Mn spinel).

sufficient degree of maturity, and the realization of a battery with a stable high energy NMC cathode (HE-NMC) is still under development.

Meanwhile, a big leap towards higher capacities on the cell level is also deemed possible by a re-design of the anode. So far, graphite has been used because dendrites were forming on the early Li metal anodes, which led to short circuits and fires in the Li batteries. With graphite, this could be avoided by safe intercalation of the Li ions in the layered carbon host.^[11] However, the capacity is reduced by this procedure from 3861 mAh g^{−1} to 372 mAh g^{−1} of the lithiated graphite, i.e., by a factor of ten. Moreover, the volumetric capacity is 2061 mAh cm^{−3} for Li metal and 1376 mAh g^{−1} for the graphite. The general aim here is therefore to replace graphite with a more powerful storage material that can also be based on a different storage principle.

Finding ways to re-establish the Li metal anode in a safe system would boost the theoretical gravimetric capacity of the anode by a factor of almost ten and one third of the space could be saved at the anode. On the cell level, this could increase the energy capacity by up to 50%,^[32,36,37] a calculation example is given by Kim.^[38] Recent work has shown a series of attempts to mitigate the risk of dendrite formation by using additives or artificial layers on the lithium, an overview is given



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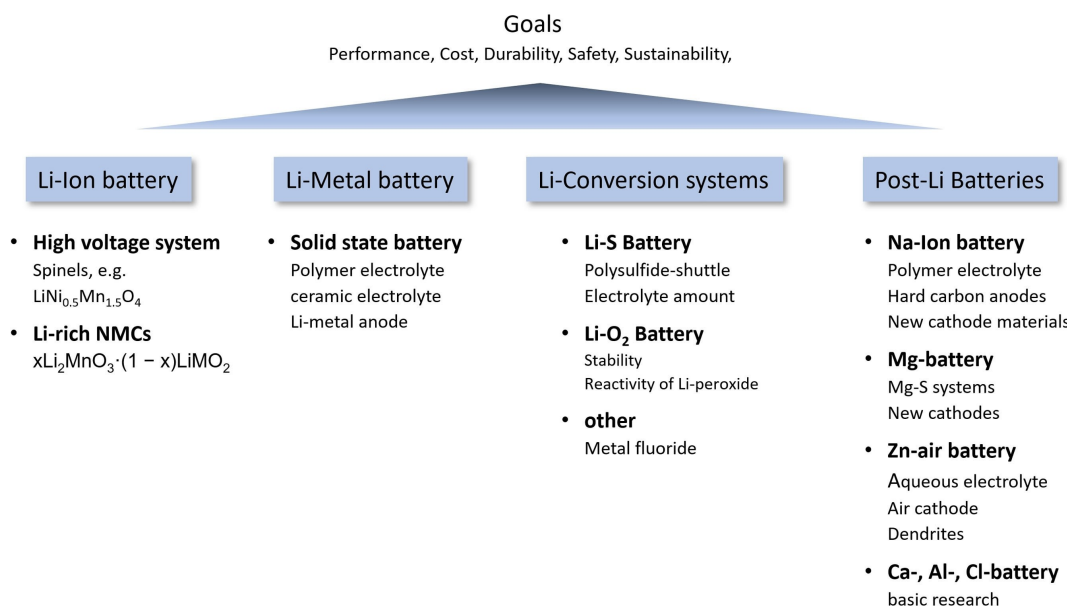


Figure 2. Overview on development routes and research topics in the battery field.

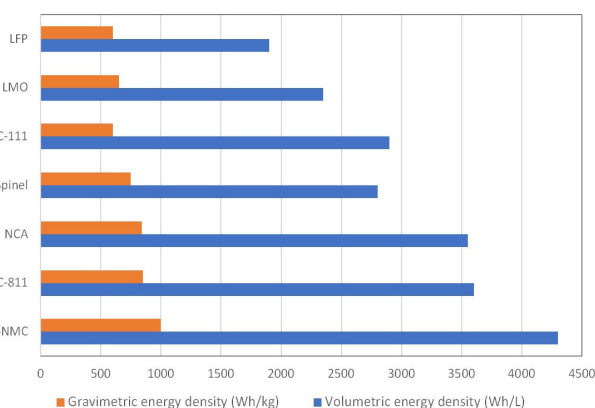


Figure 3. Gravimetric and volumetric energy densities of actual cathode materials for Li-ion batteries on a materials level. HV-Spinel and HE-NMC represent spinel $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ and $x\text{Li}_2\text{MnO}_3 \cdot (1-x)\text{LiMO}_2$ ($M=\text{Ni, Mn, Co}$), respectively.

in Aslam *et al.*^[12] However, it is not clear yet, whether one of these attempts will end up in a commercially viable and safe system. A widely studied approach to harness the high capacity of the Li metal is the solid-state battery, which may be practical in a few years and is briefly discussed below.

An alternative strategy, which is at the brink of commercialization is the switch from Li metal to alloys, which offer similar perspectives for the capacity of the anode. An abundant, non-toxic, and affordable material with very high storage capacity is silicon. In its elemental form, it reacts with Li to an alloy with the composition $\text{Li}_{22}\text{Si}_5$, which has a very high theoretical capacity of 4200 mAh g^{-1} . At room temperature, the level of lithiation is $\text{Li}_{15}\text{Si}_4$, offering a slightly lower theoretical capacity of 3578 mAh g^{-1} .^[13] In the fully charged state silicon offers higher volumetric capacity than pure Li (2190 mAh cm^{-3}). It is also safer because using Si can prevent Li dendrites from

forming. This is mainly due to the fact that Si anodes have a slightly higher lithiation potential and enable a faster Li exchange than graphite anodes. Overall, Si anodes can therefore serve as an ideal replacement for pure Li metal anodes. They offer similarly high gravimetric and volumetric capacities, but without major restrictions such as dendrite formation, unevenness of deposition, excessive reactivity, etc. For electric cars, it is also important that Si anodes offer fast charging (e.g., within minutes) at room temperature and are safe and fast even at very low temperatures.

Early attempts to build anodes based on pure Si failed because of the strong volume expansion and shrinkage during lithiation and delithiation, respectively. The cracking, breaking and pulverization of such anodes leads to short cycle life so that so far, no commercially viable anodes are available.^[8] In addition, the constant renewal of the surface through the repetitive expansion leads to a consumption of Li^+ and electrolyte, which is caused by the constant formation of new SEI layers.^[14] Numerous attempts have been made to mitigate that problem, e.g., by finding appropriate binders which could mechanically stabilize the composite.^[15–17]

A more successful attempt which has been further developed by industry in the meantime is to use porous or other carbon additives in the anode to largely prevent 'breathing' of the electrode layer.^[18,19] In first commercial systems, up to 60% Si is contained in the anode, leading to 25% higher capacity on the cell level.^[20] The silicon may be added also as understoichiometric SiO_x , which, on the one hand, lowers the capacity further but limits the volume expansion during the lithiation to 160%.^[21] Meanwhile, a series of manufacturers such as Varta, Sila Nanotechnologies, Enovix corporation, Gotion High-Tech and others are working on such composite anodes with varying, but increasing, fractions of silicon and/or SiO_x .

It is possible that advancement through this measure will result in a leap in capacity and rate capability similar to that

expected from the development of solid-state batteries. In that case, other factors such as safety and cost would play the decisive role in the race to the market.

4. Interplay of Chemistry and Engineering

This chapter deals with the advances in the development of new battery designs and their impact on future battery chemistry. To date, mostly NCA, and NMC battery chemistries have been successfully adopted by many carmakers such as Tesla, BMW, BYD, Chevrolet, Daimler/Mercedes Benz, Volkswagen, Nissan, etc.^[22] However, it is worth to mention that a major step towards more flexibility in choosing the battery chemistry and towards longer driving ranges has been made by a redesign of the battery pack and its interior as a whole.

To understand this, we should first consider the interior of most actual batteries, which consist of hundreds of individual parts. The smallest unit of the storage device, the “cells” are individually packaged plates about the size of a chocolate bar, which are joined together with others to form a “module”, which then has the shape of a large shoebox. These modules are then connected to form a large whole, the “battery pack”, which is once again protected from the outside world by a sturdy and waterproof casing. Due to the different casings and the added auxiliary materials and additives, the entire battery pack contains only 25%–30% storage material in the end. 70%–75% is therefore packaging that protects the interior of the cells and auxiliary materials that are necessary for the operation of the battery cells. Reducing this inactive fraction is now a powerful lever to achieve improved battery performance. In fact, the progress made in recent years has not only been due to the development of new and better storage materials, but above all to better utilization of the interior of the battery.

If this approach is taken a step further, one ends up with a design in which the costly production of many individual cells and modules is eliminated and instead only a few-but large-cells are accommodated in the installation space. One of the developers of this new so-called “Cell-to-Pack” (CTP) technology, the Chinese company CATL, reports that 15%–20% more storage material is housed in the same assembly-and at the same time 40% fewer parts are required for production.^[23] For example, the battery pack of the TESLA Model S contains 16 modules with 12 cells, while the new Model 3 with the CATL battery contains only 4 modules, see Figure 4. At the cell level, CATL had reached 240 Wh kg^{-1} in 2019, and targets now 350 Wh kg^{-1} for 2024.

Overall, according to the manufacturer’s statement the new Cell-To-Pack -Technology allows

- to increase specific energy by 10%–15%,
- to increase energy density by 15%–20%, and
- to reduce the number of parts for making the battery pack by 40%.

The Chinese company BYD even states that 50% more space has been created for the cathode material, in its new so-called “Blade Battery”. Moreover, at the “Battery Day” of TESLA

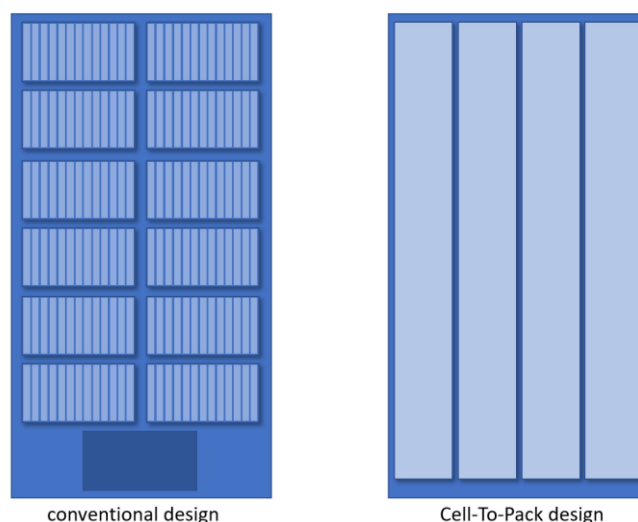


Figure 4. Schematic representation of the design of a conventional battery pack (left) with that of a cell-to-pack design (right). The cells are in light blue, the housing and control unit are in dark blue.

in September 2020 it was shown that by changing the battery format from the former 18650 cell to the new, significantly larger 46800 cell format, an increase of 16%–18% may be possible. It is interesting to note that, in the projected range increase of 54% in TESLA’s Vertical Integration, the contribution by new chemistries is only 24%. The majority of the improvement is expected from the engineering. Moreover, from the targeted cost reduction per kWh of 56%, one third is due to chemistry and two thirds due to engineering.

This has far-reaching consequences. For the driving range, the rate capability, the sustainability of a battery and especially for the costs and safety.

5. Is There a Twilight of Materials?

If the battery chemistry is left as it is and the new design is used, 100 km of range or more can be gained, depending on the CTP design and the size of the battery.

However, the space gained can also be used to put the battery on a more sustainable material basis. In particular, this could make expensive and sometimes toxic heavy metals such as cobalt, which has come under criticism, but also nickel, obsolete. Lithium iron phosphate (LFP) as a potential alternative material is abundant, safe, inexpensive is already widely used in commercial applications. It is currently mainly utilized in home storage systems for PV systems, in busses - but also in Formula 1 in the so-called KERS (kinetic energy recovery system) technology. So far, it has not been used in passenger cars mainly due to its low density (3.47 g cm^{-3}). The light weight is a seeming advantage, but in practice this turns out to be a disadvantage when you consider that the same amount of iron phosphate takes up almost twice as much space as cobalt oxide (approx. 6 g cm^{-3}). NMC and NCA materials, which contain about 3%–20% cobalt, are also more compact. In short,

the iron phosphate simply did not offer enough range until now due to its high space requirements.

With the new CTP designs, more iron phosphate or other light material can now be accommodated in the pack, thus gaining all the benefits in terms of cost, sustainability, and safety without having to accept shorter ranges. The blade battery mentioned above provides 600 km of range for their sedan. In nail penetration tests the battery did not get hot or is catching fire. Moreover, it is considerably cheaper due to its simpler construction, and less parts. In addition, the prize of LFP is only a fraction of that of current NMC, so that the batteries will be much cheaper than the current ones. As an effect, a series of car manufacturers have announced new BEV models on the basis of the LFP technology, including Tesla, Volkswagen, Renault, Ford, and others.

Another beneficial aspect is that the iron phosphate is also more durable than other materials. With the current NMC materials in the cathode, 2000 full cycles are standard until the end-of-life criterion of 80% capacity is reached. With LFP, 5000 to 10000 cycles are possible, or a range of several million kilometers. This makes the technology particularly suitable as future autonomous fleet vehicles with mileages of 150,000 km per year each. A BEV will then be several times more profitable than a car with a combustion engine, which has a service life of only 300,000 km. This is not only lucrative for the operators of autonomous fleets, but also for private customers. If the driver wants to switch to another model after driving 200,000 km, then the battery is still almost new and has a high resale value, which further reduces the overall costs of the vehicle.

6. Outlook

6.1. New Engineering Concepts

The CTP technology is obviously not the last step in improvement of the electric car by engineering. Meanwhile, the technology leaders are also working on the so-called Cell-To-Chassis (CTC) technology, where the cells shall be integrated directly within the vehicle frame. By dispensing with modules and packs, more cells fit in the same installation space. And more cells mean more range. With the new technology, it should be possible to realize electric vehicles with a range of over 800 km, which shall be no more expensive than cars with internal combustion engines. The integration of the battery cells into the vehicle structure is supposed to save up to 40% in construction volume compared to today's production methods. In 2020, CATL announced a schedule for CTC technology, with a plan to start series production as early as 2025.^[24]

6.2. New Chemistries

There are concerns that the use of critical raw materials such as cobalt, lithium and graphite, but also nickel may lead to shortage of supply when the demand for newly manufactured

car batteries continues to incline. For Co and Ni-based materials it was shown that there may already be more sustainable (but less energetic) alternatives such as LFP or LMO. Moreover, natural graphite can be substituted by synthetic graphite.

That leaves the shuttle ion lithium, which can only be replaced if the entire battery chemistry is rethought and re-developed from scratch. With the goal to find and develop appropriate solutions for cathode and anode materials, collectors, separators, and, in particular, electrolytes, an entire new battery field has grown which deals exactly with those issues, the field of post-lithium batteries. The idea is basically to replace the monovalent Li ion by other monovalent ions such as Na- or K-ion, or by multivalent ions such as Mg-, Ca-, Zn-, or Al-ions. Even anionic shuttle ions are considered.^[25] Figure 5 compares materials-related theoretical values of gravimetric and volumetric capacities of various post-Li anodes with those of lithium. The Figure shows, that the theoretical numbers promise a high potential of the alternatives, however, it has been shown that it may be a challenge to reach these values in practice.^[35] Moreover, the state of development differs of the various candidates and most of them are still in the laboratory stage and have TRLs not higher as 5 – with one exception, the sodium ion battery.

Na technology has the highest technical maturity of all candidates. It is the first post-Li candidate which has been commercialized and is deemed suitable for various applications, including electric vehicles.^[27] In June 2021, the world largest battery manufacturer, CATL, announced to mass-produce SIB with the aim to replace previous batteries in various applications. According to official information, one goal is to substitute the lead-acid battery in current ICE vehicles, then batteries for two- and three-wheelers shall be produced, and finally large applications such as stationary storage and electric vehicles will be targeted.

Sodium ion is monovalent, it is heavier and bigger than lithium ion and the cell voltage is somewhat lower compared to LIBs. This is why the energy density and energy capacity of current sodium ion batteries (SIB) is below that of an LIB. To overcome this issue, further development will be necessary towards finding more efficient host structures which enable

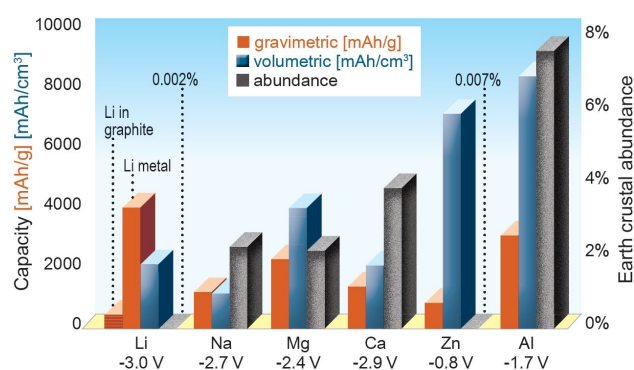


Figure 5. Comparison between gravimetric and volumetric capacities, standard reduction potential and earth crust abundance of metal anodes used or proposed for application in electrochemical storage systems (reproduced with data from Ref. [26]).

denser packing of Na^+ . In addition, the first cycle losses need to be addressed which are too large at the moment. Another field of development is the cyclic stability. With SIBs, the end-of-life criterion of 80% residual capacity is reached at around 1000 cycles. This is below that of LIBs, which reach 2000–3000 cycles, depending on the chemistry.

However, there are also intrinsic advantages which come from the fact that Na^+ is a comparably soft ion, which may be even better mobile than Li^+ , a feature that is needed for power tools, for example and allows fast charging. A clear advantage is the high residual capacity of SIB at low temperatures. LIBs with NMC or NMX-based cathodes deliver around 70% of the nominal capacity at -20°C and Li-iron phosphate delivers only 60%. In contrast, SIB offer a residual capacity of 90%, which is superior to the Li-based chemistries.^[28] There are plans to combine SIB and LIB in one battery pack in order to benefit from the properties of both chemistries under various operation conditions.^[28]

Another clear advantage is the projected cost of SIB which is estimated to be only 40% of an NMC-based LIB. From the viewpoint of sustainability, SIB do not need Co or Ni in their cathodes, the Cu collector in LIB anodes can be replaced by the much more abundant Al and the anode is made of synthetic hard carbon which can be produced from residual biomass.^[29] Finally, a critical feature is also that the fabrication of cells is very similar to the fabrication of LIB cells, so that SIB is also called a “drop-in” technology.

A current industrial SIB cell is made with a hard carbon anode and a “Prussian White” cathode. Prussian White is the sodiated version of the pigment Prussian Blue, $\text{Fe}^{\text{III}}_4[\text{Fe}^{\text{II}}(\text{CN})_6]_3$, a synthetic pigment which is non-toxic and inexpensive. According to the manufacturer CATL, the energy capacity is 160 Wh kg^{-1} on the cell level, which is considerably lower than the 200 Wh kg^{-1} of LIB cells with LFP cathode. Interestingly, the difference is not so large with respect to the energy density, where the SIB offers 300 Wh L^{-1} compared to 350 Wh L^{-1} of an LFP based cell. While the numbers do not seem competitive at the moment, a next generation of SIB has been announced for 2022, with 200 Wh kg^{-1} , i.e., in the range of LFP based cells. The battery manufacturer also claims that, due to the better thermal properties of the SIB, as denser arrangement of cells is possible in the pack, thus making higher energy densities possible on the pack level.

This, together with the better residual capacities at low temperatures and the considerably lower materials cost, renders future SIB also potential candidates for traction batteries.

6.3. Further Approaches

An outlook may not be complete without referring also to other chemistries, which have been considered as potential candidates or even as ultimate solution for batteries in electric vehicles. Most of these chemistries have not reached a satisfactory technology readiness level, yet, and it is unclear,

when or whether at all an industrially relevant readiness will be reached for car batteries.

6.3.1. Lithium-Air Batteries

The Li-air battery is based on a battery chemistry where lithium is oxidized at the anode and oxygen is reduced at the cathode. In the early 2010's this system has been termed as “holy grail” in batteries, because the reaction of Li metal with oxygen into lithium peroxide (Li_2O_2) can theoretically deliver the highest possible specific energy (3500 Wh kg^{-1} based on Li_2O_2 formation at the cathode).^[30] Unfortunately, the system suffers from a vast number of challenges, for example side reactions which are mostly caused by the high oxidative strength of the discharge product Li_2O_2 . The peroxide can oxidize organic materials on contact and attacks electrolyte and the carbonaceous catalyst support in the cathode.

Under certain conditions, it may ignite organic compounds and react explosively with hydrocarbons. And even without reaction partners, it may explode when heated in a closed container. It is evident that such risks would have to be mitigated or eliminated in any commercial product.

Moreover, the lithium metal reacts not only with O_2 but also with other components of ambient air such as H_2O , or CO_2 , which would have to be filtered out to avoid irreversible reactions. Therefore, only oxygen in a mixture with unreactive gases is used in laboratory experiments. Due to the necessary auxiliary units and due to the limited areal capacity of the system, full cells are not expected to reach more than 400–450 Wh kg^{-1} in practice.^[30]

6.3.2. Lithium-Sulfur Batteries

When a lithium-sulfur (Li–S) battery discharges, lithium is oxidized at the anode while sulfur is reduced in several stages from S_8 ring to sulfide, forming solid Li_2S inside an electrically conducting matrix. While the theoretical capacity (1675 mAh g^{-1}) and specific energy (2567 Wh kg^{-1}) are high of this system, there are several contributors which add inactive weight and volume and dilute the active material. One is the large amount of a conductive matrix, mostly carbon, which is necessary due to the strong insulating nature of sulfur. Another factor is the typically high amount of electrolyte, which can be necessary because the electrolyte may degrade in side reactions with polysulfide intermediates and the battery can dry out. Various degradation effects, which are typically associated with the polysulfide intermediate have so far limited the reversibility of practical systems to several hundred cycles.

One feature of Li–S cells is that they may have high gravimetric capacities, in the order of 350 Wh kg^{-1} for real systems.^[31] However, due to the light weight of the used materials, the volumetric capacity is comparably low so that Li–S chemistry is mostly considered for airborne or space applications. In recent years, several companies such as OXIS Energy or Sion Power have offered prototype systems. How-

ever, OXIS Energy is insolvent meanwhile and Sion Power has diversified towards the development of Li metal batteries.

6.3.3. Lithium-Metal Battery

As already mentioned above, it is a goal to build the LIB with a Li metal anode, because this would boost the anodic capacity from 372 mAh g^{-1} to 3861 mAh g^{-1} . The associated increase of the capacity of the battery pack is estimated as 30%–40%. For realization of this goal the so-called Solid State Battery (SSB) is envisaged which is associated with several advantages or expectations:

- higher storage capacity/longer driving range
- higher rate capability/faster charging
- improved safety/ban of combustible organic liquids

Characteristic for the currently developed designs is that the cathode is more or less identical to that of the conventional LIB, while the liquid electrolyte is replaced by a polymeric or inorganic electrolyte, the latter being based on oxides or sulfides. The anode is either Li metal in excess or Li metal generated *in-situ* during charging on an otherwise empty collector foil. A major advantage is that the solid electrolyte shall act not only as ionic transfer medium but also serves as mechanical barrier for the growth of dendrites, which would otherwise grow from anode to the cathode and lead to shortcuts and failure.^[32,33]

The major challenges in this field are to provide sufficient ionic conductivity in the various parts of the cell, and to enable and maintain an intimate contact of the various functional materials in the electrode composite and between the electrode and the solid electrolyte. It is far than trivial to maintain this solid-solid interface contact over hundreds or thousands of cycles because of the expansion and shrinkage of the active materials during charge and discharge. Many promising results were obtained with laboratory cells that were kept under a high external pressure of several 10 to 100 s of bars. For a commercial application, this is not a viable solution, however. To mitigate potential disruption or build-up of interfacial resistances it has been shown that thin intermediate layers of ionic liquids in small amounts can act as mediating agent on the micro- and nanometre scale.^[34]

A large number of research groups and companies is working on the realization of SSB. From time to time, there are press releases where a technical breakthrough is announced. However, often only part of the data and experimental conditions is given so that it is difficult to judge the actual technical state-of-the art and readiness level of the respective system. Rather, a great difference in the various announcements of ready-to-commercialize systems can be noticed, which may be due to the fact that the long transition between laboratory cells and large industrial formats in mass production is underestimated. This is a particular challenge if the cell is built from thin ceramic layers which must stay in perfect contact and be free of defects. Moreover, it seems that the announcements underestimate the lead time which is needed by car manufacturers before the new battery can be integrated

in the car. Given these uncertainties and given the fact that no industry-ready SSB has been tested on its properties, it is unclear when the SSB will reach the market and whether it will be competitive to the “conventional” LIB, which will also make progress in the meantime. From the current state-of-the art, a commercialization can be expected not before 2025.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: cell-to-pack design · electric vehicle · lithium ion battery · lithium iron phosphate · post-lithium system

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