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Review paper

Can the development of batteries keep pace with the ever-increasing demands of consumers?

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Abstract

The global production of batteries, in terms of total energy content, is continuously increasing to meet consumer demands. Many gigafactories all over the world have been established to sustain the supply chain, together with smaller production lines to meet the requirements of some specific, niche applications. China is the global leader in battery production, with a worldwide production network. While the battery supply balances their demand, their performances, which are equally important to sustain the development of the society based on renewables, increase at a slower pace than the requirements of different applications. In this article, we overview the present state of battery development, indicate major limitations of the present technologies and identify bottlenecks for their further development.

Keywords

Lithium-ion batteries; solid-state batteries; lithium metal batteries; post-lithium technologies; sodium batteries; magnesium batteries; calcium batteries

Introduction

Demand for electrochemical energy conversion and storage devices has continuously increased over the years, especially with the evolution of electric vehicles and mobile devices. It has been met by the expansion of manufacturing facilities worldwide, witnessing the steady increase in the number of lithium-ion battery (LIB) gigafactories and small regional production plants to sustain the supply chain for smaller customers and niche applications. Major Chinese large-scale gigafactory companies, such as CATL and BYD, are spreading their manufacturing network worldwide, targeting capacities high enough to sustain the supply chain. Currently, there are six gigafactories in Europe with an estimated storage capability of 250 GWh annually. Such a rapid increase in energy storage capacities has led to overexpansion, resulting in the suspension of some productions in China and Europe [1,2].

In parallel, and at least equally important, there is continuous pressure to meet the ever-increasing battery key performance indicators (KPIs). KPIs are a set of targeted values of specific parameters relevant to battery performance. The major indicators mostly considered are gravimetric and volumetric energy density, available power at defined energy output, and cycle life. Batteries Europe (https://batterieseurope.eu/), as a platform gathering all relevant parties to foster the competitive battery value chain, annually publishes KPI benchmarking to accelerate the establishment of the road map to support the European Strategic Energy Technology plan that will enable sustainable energy transition of the society [3]. While relatively simple methodologies can do the performance assessment of battery cells and battery packs, the values that can be found in the literature largely vary. The lack of good quality data comes from (i) variation in the testing methodologies, (ii) biased evaluation of the obtained data and (iii) intentional exaggeration of the battery performance parameters for the sake of competitiveness, usually from manufacturing companies. Recently, Battery Europe suggested methodology guidelines that enable the proper comparison of different battery technologies and ensure accurate and reliable data [4].

Electric vehicle manufacturers are major consumers of batteries nowadays. Vehicle performance is directly related to the performance of batteries, and this relationship is a primary focus of all car industries. This is so important that many car manufacturers, such as Tesla or BYD, have established their own battery production facilities. The most common features characterizing electric cars are driving distance, which is linked to the battery energy density, acceleration, which depends on the power density and cyclelife, reflecting reversibility and coulombic efficiencies of the cells. All three parameters depend on the battery pack size, *i.e.* its mass. While it is generally accepted that the average range for today's electric vehicles is about 400 km, many other quoted values up to 800 and even 1000 km can be found on the internet. Realistically, they reflect more wishful thinking than reliable values that can be reproduced in actual urban or highway driving conditions.

Practical energy density varies depending on battery cell chemistry. Even within the same cell chemistry, the values might differ for different technologies. For example, two commonly used chemistries in electric vehicles, NMC (Li/nickel-manganese-cobalt oxides) and LFP (Li/$LiFePO_4$), span the ranges of practical energy density between 200 to 250 Wh kg^{-1} and 150 to 180 Wh kg^{-1}, respectively, on a single cell basis [5]. This would be the maximum limit for battery packs and expected pack values would be even lower. The energy consumption of the average medium-sized car of 1500 kg goes up to 0.2 kWh km^{-1}. Consequently, a road route from London to Paris, which is a trip of roughly 400 km, requires a battery of at least 80 kWh without stopping for refuelling. Spare capacity of at least 25 % should be added, and the inevitable battery aging, leading to capacitance deterioration, should be taken into account. This means that in the mentioned case, a battery of 125 kWh would be optimal to ensure a convenient and reliable distance range. If we consider the best theoretical battery energy density of 250 Wh/kg, the battery weight would amount to 500 kg. We should add this weight to the weight of the car with which we started this calculation. Considering that electric cars are usually heavier than comparable gasoline cars due to the chassis reinforcements and integrated extra cooling systems, a battery of 500 kg would not suffice to accomplish the task. Even if we consider high-end battery models of 300 Wh/kg claimed by some manufacturers, a 500 kg battery would still be required. As these practical values of energy densities are still insufficient for modern car industries, the EU and NASA are committed to developing high energy densities exceeding 400 Wh kg^{-1} to sustain the smooth transition to the electrified transportation sector and to meet the evolving needs of the automotive industry. European Battery Alliance (EBA), in its Strategic Research and Innovation Agenda (SRIA), set a goal of 400 Wh kg_{-1} at the cell level [6]. The target for 500 Wh kg^{-1} aerospace applications is even more rigorous [7].

Increasing LIB performance is a slow and challenging job. Figure 1 shows the evolution of LIB gravimetric energy density from the early ‘90s until the present. A steady increase in energy density with an average rate of 5 Wh kg^{-1} annually is observed. While this significantly improved electrified transport over the years, it is still too slow to meet the ambitious goals of EBA and NASA. It is not practical for humankind to wait for the next decade or two to reach the required level of energy density with such an incremental improvement. Instead, a jump increase is expected, and this might eventually be possible only with the rise of new technologies to a level that is acceptable for commercialization. In the same way that the advent of LIBs revolutionized the energy sector, new battery technology should move from research labs and position itself as a viable, improved alternative to current LIBs.

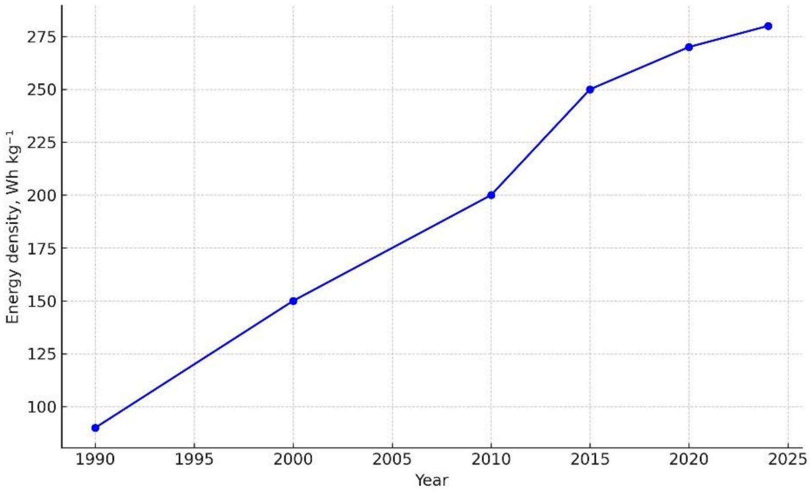

***Figure 1**. Evolution of gravimetric energy density over the last three decades [8]*

The present state of energy density today is partly due to the development of efficient battery management systems (BMS), which are indispensable to control and manage the energy flows within different parts of the system. BMS optimizes the performance and cycle life of batteries, which is even more important for cell balancing in battery packs, where a large number of single cells, for some electric cars more than 1000, are combined into the system, in which each cell should be rigorously controlled to provide maximum energy. While the BMS does not directly increase the gravimetric energy stored in the battery, it enables it to operate closer to its maximum capacity without compromising safety or cyclelife.

The major role in the continuous development of LIB energy density over the years, as demonstrated in Figure 1, plays electrochemical engineering, which bridges the interdisciplinary fields combining electrochemistry, material science and material engineering, electrical engineering, and it includes cell design and construction. Despite many different approaches to controlling and managing battery cells in packs to maximize available power and energy and minimize aging effects, improving cell chemistry is still a key issue. For example, the specific energy is a product of specific capacity and voltage, Equation (1):

$$E_\mathrm{s} = Q_\mathrm{s}U \tag{1}$$

where the voltage is the difference between the individual electrochemical potentials of positive and negative electrodes (E_c-E_a) and Q_s, the specific capacity.

All approaches to developing high-energy-density battery cells rely on this equation, which looks very simple on the surface. We should increase either specific capacity or battery voltage. However, in practice, it is far from being simple. Here, improving the battery performance is directly related to cell chemistry, which is difficult because we are limited by chemical thermodynamics and electrochemical kinetics. Both directly determine the cell performance, how much energy it stores and how fast it can be liberated, providing power. If we want to increase the voltage beyond 5 V, we should design high-voltage cathodes and, at the same time, have electrochemically stable electrolytes compatible with both electrodes. If we want to store more charge at unit weight or volume, we should focus on the crystal structure and new materials.

In principle, an energy density of 250 Wh kg^{-1} represents the highest practical limit we could achieve today. It is, of course, possible to boost the performance of batteries by pushing their charge or discharge to higher voltages. Another way is to coat the current collectors with more active materials, increasing the available charge without significantly increasing the mass of the cell. This is exactly what happens with the high-end battery models with specific energies allegedly going up to 300 Wh kg^{-1}. However, as a rule of thumb, it is not possible to improve one battery parameter and keep the other parameters fixed. Increasing specific energy comes at the expense of cycle life or the available power. One has to optimize the design of the cell, keeping in mind a potential application.

Increasing production and achieving a set of KPIs for batteries is just one aspect of the requirements that battery technologies must meet to continue supporting the high demands of today's complex applications. Their use also raises several ecological, socio-economic, and recycling concerns, as lithium and other metals like cobalt and nickel are scarce and scattered worldwide, creating geopolitical tensions.

Extracting lithium, cobalt, and nickel causes deforestation, soil and water pollution even if appropriate precautions are implemented to minimize them. Also, lithium-ion batteries contain toxic waste, which can contaminate the environment. Unfortunately, despite the noticeable progress of recycling technologies, they are still not cost-effective, adding to the total cost of battery production. Special attention is paid to the circular economy approach, to use spent batteries in second-life applications, repurposing them for energy storage before full recycling.

To overcome the present issues with lithium-ion technologies, a lot of research efforts have been made and a lot of funds invested to find suitable alternatives to alleviate the challenges of lithium-ion batteries and to minimize concerns about their usage. The potential promising alternatives include solid-state batteries, lithium metal batteries and post-lithium technologies.

Solid-state batteries

Novel all-solid-state batteries (ASSBs) represent an emerging battery technology that replaces current liquid electrolytes (LE) with solid electrolytes (SE). This change brings some unique characteristics and benefits but also challenges. ASSBs can overcome the issues related to efficient and well-developed LIBs, resolving the problems of electrolyte decomposition and dendrite formation, which are potential causes of short circuits and fires [9,10].

ASSB can achieve higher energy densities, sometimes reaching double the values of LIB, meaning that they can acquire more capacity in the same volume or weight, which is important for EVs and portable electronics. Another advantage is longer cycling life and lower degradation over time compared to liquid-electrolyte batteries. What puts solid-state batteries ahead of lithium-ion batteries is safety, because solid-state electrolytes reduce the risks of leaks, fires, or explosions. An additional fact that favours safety is a wider operating temperature range and safe operation at higher temperatures [11]. A very important advantage of ASSBs is that a pure metal anode can be used, allowing the ultra-compact designs and high energy density. The following numbers prove that ASSBs can really replace LIBs: LIB based on NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) versus graphite achieves an energy density and a specific energy of 635 Wh l^{-1} and 265 Wh kg^{-1}, respectively. In comparison, an SSB with NCA versus lithium metal may theoretically reach 1143 Wh l^{-1} and 393 Wh kg^{-1}, respectively [12].

The selection of materials in solid-state batteries depends upon cost, performance, and safety considerations. The most commonly used cathode materials in ASSB are metal oxides or sulphides, particularly those based on layered compounds. In particular, mixed transition metal (TM) oxides can deliver specific energy densities ranging from 500 to 800 Wh kg^{-1}. The most common anode materials, which are similar to those used in batteries containing the LE, include metal alloys, hard carbon, expanded graphite (EG) and various metal oxides; among these, the most popular is the lithium metal anode. For example, the Li metal anode has a high theoretical capacity of 3860 mAh g^{-1} and a low electrochemical potential of -3.04 V versus the standard hydrogen potential [13,14]. Nonetheless, Li metal anodes face substantial obstacles that limit their practical use, such as low coulombic efficiency and the formation of lithium dendrites during cycling, which can lead to internal short circuits, capacity deterioration, and safety hazards. These factors significantly hinder the long-term stability of lithium-metal-based solid-state batteries by increasing overpotential and capacity degradation. To address these issues, composite electrodes are introduced, such as Si-Li.

The most challenging task is to design an SE capable of conducting ions at room temperatures, exhibiting a sufficiently high ionic conductivity above 10^{-3} S cm^{-1} and low activation energy [15-18]. In solid-state configurations using a lithium metal anode, the solid electrolyte must maintain stability against chemical and electrochemical reactions with lithium while effectively suppressing the propagation of metallic lithium dendrites. It should possess a wide and stable electrochemical window to accommodate various types of active materials. An additional requirement is that it must be cost-effective, facile in fabrication, and meet severe mechanical and chemical stability requirements, as well as have a large thermal stability window, excellent mechanical properties, and high conductivity. To date, no lithium solid electrolyte has satisfied all of these criteria, and achieving stability during cycling with lithium metal remains a critical challenge. Considering the pros and cons of various types of electrolytes, the best solution is to form a composite electrolyte [19].

The main challenge is the requirement of elevated temperatures to achieve appreciable ionic conductivity. Thio-LISICONs (LGPS) held a record (12 mS cm^{-1}) for room-temperature Li-ion conductivity in solid state from 2011 till last year, when the current record of room temperature Li^+ conductivity of 32 mS cm^{-1} in a hot-pressed sulfide ($Li_{20/3}(GeSiSb)_{1/3}S_5I$) was confirmed and reported in a paper by Ma and coauthors [20]. These values even surpass those of liquid electrolytes.

Solid-state batteries today are at about the same stage of development as LIBs were a decade ago, so there is considerable room for their development. Although commercialization is still in progress, numerous companies are making substantial advances in integrating solid-state battery technology into electric vehicles [21]. Chinese company IM Motor produced the first car with a solid-state battery (or semi-solid-state), the IM L6, featuring a 123.7 kWh battery pack, a range of 1,002 km, and support for 400 kW ultra-fast charging. However, some of the specifications, such as 1,000 km range according to the China light-duty vehicle test cycle (CLTC) standard in China, tend to be optimistic, while under more conservative standards, *e.g.* worldwide harmonised light vehicle test procedure (WLTP) or U.S. Environmental Protection Agency (EPA), the real range will be lower. IM themselves claim around 800 km WLTP for this version. To support 400 kW ultra-fast charging, we need compatible charging stations (both power supply, cooling, connector, *etc*.). These are still not widely available everywhere. Without proper infrastructure, the fast charge claim is less useful for many users. Certain prototype cells exhibited over 1000 charge cycles while maintaining over 95 % capacity retention, equating to over 480 km of driving. Semi-solid-state batteries that can fast-charge from 15 to 90 % in 18 minutes and perform reliably in temperatures ranging from -30 to 45 °C are also under research. The prices of ASSB batteries are currently significantly higher than those of conventional Li-ion batteries. This is because ASSB technology is not yet widely commercially available, solid electrolytes are more expensive and complex to process, and there are still technological challenges related to cycle stability, interlayer contact, and scalability. When discussing numbers, the mass production of Li-ion batteries results in a price of around 100 to 150 $ *per* kWh, whereas for ASSB, this price is around 200 to 400 $ *per* kWh. Nissan intends to decrease battery pack costs to 75 $ *per* kWh by 2028, with a possible further reduction to 65 $ *per* kWh to achieve price equivalence with internal combustion vehicles. Although these numbers sound attractive, Samsung SDI has put forth more realistic goals, with analysts expecting ASSB prices to equal Li-ion batteries by 2028, at around 110 $ *per* kWh.

Undoubtedly, ASSBs will significantly influence the future. Lithium-ion batteries remain the standard owing to their established durability and cost-effectiveness; however, they may ultimately be replaced or expanded by solid-state batteries, particularly in high-performance electric vehicles and aerospace applications. Solid-state batteries are considered a game-changer in EVs due to their potential for enhanced energy density, improved performance, and safety. Solid-state batteries could enable the development of thinner and longer-lasting devices in consumer electronics, as well as long-term, high-capacity storage solutions for grid applications; however, they currently face constraints related to cost and manufacturability. The intrinsic rigidity of both the cathode and the solid electrolyte, combined with the limited interfacial contact area, results in poor solid-solid interfacial contact and thus high interfacial resistance [22]. Additionally, solid electrolytes readily react with active materials and decompose across a wide potential range, forming resistive, often redox-active interphases. This challenge can be mitigated by employing composite cathodes, in which uniform distribution and/or particle size reduction enhance interfacial connectivity [23]. Protective interphase layers are also often introduced. In-situ and operando techniques could help with understanding and implementing the interfaces between electrodes and SSEs. Volumetric variations on the anode side are caused by the repetitive plating and stripping processes, which lead to deteriorated contact and increased resistance. The construction of composite materials can help overcome this problem. Although everyday advancements in the field of solid-state electrolytes and batteries in general are huge, there is still no solution in the form of commercially viable ASSBs capable of meeting the growing demands of modern society. Even though the existing solutions have values that can be acceptable for early adopters, manufacturers will need to show long-term reliability, cost reductions, and infrastructure support for broad market success.

Lithium metal batteries

Lithium metal batteries (LMBs) are not a new concept, as lithium as an anode has been well established and used in primary lithium cells for a long time. Lithium metal is mechanically malleable, possesses the highest theoretical specific capacity of approximately 3.860 Ah g^{-1} and exhibits the lowest known reduction potential (-3.04 V *vs.* SHE). Because of these properties, lithium metal is considered the best anode material in terms of energy and weight. Similar to other metal-based battery chemistries (*e.g.* zinc, lead), using lithium in metallic form maximizes energy density at the cell level. Furthermore, charge-transfer kinetics at the lithium/electrolyte interface are fast, enabling rapid charging and discharging. Modifications of the surface or structure of metallic lithium anode, such as alloying, intercalation hosts, or other approaches, reduce its achievable specific capacity and often complicate the interfacial reaction. For example, graphite, which is today almost exclusively used in commercial lithium-ion batteries as the intercalation host, decreases the available specific capacity of an anode by almost 10 times and the reduction potential by approximately 200 mV compared to metallic lithium.

Despite its theoretical advantages, the practical realization of rechargeable LMBs is hindered by Li interfacial instability. Lithium is highly reactive and prone to decomposing any electrolyte components with which it comes into contact. This process is similar to the metallic corrosion, which results in the formation of a solid-electrolyte interphase (SEI) that passivates the lithium surface and protects it from further dissolution. Luckily, the SEI formed on lithium is usually electronically insulating but ionically conductive, passivating the anode while maintaining Li^+ transport at a sufficient rate to enable high-rate applications. In practice, however, the spontaneously formed SEI is a heterogeneous layer, mechanically fragile, and undergoes repeated rupture and reformation during lithium plating and stripping. When there is a variation in current density across the electrode area, non-uniform Li^+ concentration and ion flux, a non-uniform lithium deposition occurs, resulting in the nucleation and growth of dendrites at more reactive lithium active sites [24]. Dendrites are needle-like metallic crystallites that protrude from the lithium surface, penetrating the membrane. These dendrites degrade capacity via the formation of "dead lithium," diminish Coulombic efficiency, but, most importantly, compromise safety through the danger of creating internal short circuits, which might seriously damage the cell and lead to fire or explosion. Additionally, continuous SEI reformation consumes both active lithium and electrolyte, leading to the rapid cell degradation over repeated cycles.

There have been many research efforts to control the interface and limit dendritic growth [25]. These include the use of electrolyte additives, preformation of a favourable artificial SEI layer or the design of a charging protocol that would minimize the concentration inhomogenities at the lithium surface.

1. Electrolyte additives are the most straightforward approach to the formation of uniform lithium layers during their deposition and stripping [26,27]. Their function is either to ensure a uniform current density over the whole electrode by preadsorbing on those surface active sites that protrude from the electrode surface deeper into the electrolyte or to influence the composition of SEI, promoting inorganic components to enhance mechanical and/or chemical stability. Compounds such as vinylene carbonate and fluoroethylene carbonate (FEC) [27-31], lithium nitrate ($LiNO_3$) [31-33] or lithium halides [34] are the most commonly investigated compounds for this purpose.
2. Another approach is to cover the lithium surface with protective coatings, either polymeric or ceramic, before cycling, to provide a chemically stable interface. A good coating should reduce electrolyte decomposition and enable more uniform Li deposition. Artificial SEI layers often have a significant portion of inorganic compounds, such as LiF-rich [35,36] and its composites or polymer-inorganic hybrid coatings [37,38], designed to prevent dendrite nucleation. Good artificial SEI coatings should be able to provide a uniform lithium ion transport across the electrode area. Surface modification techniques include atomic or molecular layer deposition (ALD, MLD) [39], plasma treatments [40], or functionalization with lithiophilic materials like graphene oxide [41] or boron nitride [42] nanosheets to improve interfacial adhesion and homogenize current distribution at the electrode-electrolyte interface.

3. Implementation of charging protocols, such as applying pulse charging or fast ramp charging, might significantly influence dendrite nucleation and growth. Pulse charging is an engineering methodology that has been used for a long time to obtain evenly distributed protective or decorative layers of metals or other substances on the same or foreign support. The idea is to achieve a thin diffusion layer and, in such a way, reduce concentration polarization, leading to more uniform ion flux across the surface. The pulse currents are several times and maybe an order of magnitude higher than those applied during conventional DC charging conditions. Although the charging time in these two charging approaches might be the same, pulse charging creates much thinner diffusion layers, resulting in a more uniform flux of lithium ions over the electrode surface. This way, the time-averaged local current density remains below the critical threshold for dendrite nucleation. Although the pulse charging approach has great potential, its interplay with the mechanical properties of the forming SEI layers is still to be elucidated and demonstrated.

Combined implementation of these approaches shows promise, but complete stabilization of SEI under practical conditions remains challenging. There are several good review articles written on lithium metal batteries [33,43-45].

Post-lithium battery technologies

One of the possible directions to alleviate problems associated with the present status of lithium batteries is to completely move from lithium technologies to other chemistries, which might perform better or at least as well as lithium-ion batteries. One reasonable alternative is to replace lithium with other alkali metals, such as sodium or potassium. Metals that exist in multivalent states, such as alkaline earth metals or aluminium and zinc, are another option. All these systems offer considerable advantages, but overall, inherent problems with their chemistry, the structure and permeability of passivating layers on their surface and kinetics limit their widespread practical application [46]. Up to our knowledge, only sodium batteries emerged recently as commercial models [47,48]. Although they hold a good promise for the post-lithium era, current rate capabilities and energy densities must be further improved.

Among these multivalent systems, calcium and magnesium have attracted particular attention due to their divalent charge, which allows transfer of two electrons per ion, resulting in higher theoretical values of energy density. Calcium offers a relatively low redox potential (-2.87 V *vs.* SHE) [49], a high volumetric capacity (2073 mAh cm^{-3}) [50], and a high melting point (842 °C) [51], in addition to its natural abundance, which makes it a safe, cost-effective and attractive candidate for large-scale commercialization. Nevertheless, the practical application of the calcium battery is limited by the formation of the passivation layer that hinders the ion transport. Besides, relatively larger cations, in comparison to lithium and sodium [52], result in sluggish diffusion kinetics, thus reducing the power output and cycling performance [53]. Similar to calcium, magnesium stands out due to its low reduction potential (-2,37 V *vs.* SHE) [54], high volumetric capacity (3833 mAh cm^{-3}) [55], high specific capacity (2252 mAh g^{-1}) [56], and a more than 1000 times higher abundance than that of lithium [57]. Furthermore, the magnesium electrode is considered a safer option than the lithium one since magnesium is less prone to the formation of dendrites [58], making magnesium an appealing alternative to current lithium-ion batteries. In a manner similar to the calcium battery, magnesium encounters comparable obstacles to commercialization, as it reacts with simple magnesium salts and common solvents used in battery research, forming a passive layer that hinders Mg^{2+} ion diffusion. There are several groups of electrolytes that enable reversible plating/

/stripping, but most of them are highly corrosive to battery components like gaskets, cases and current collectors [59]. On the other hand, aluminium and zinc also show significant potential for battery applications. Aluminium's trivalent redox chemistry enables high volumetric capacity (8046 mAh cm^{-3}) [60] and theoretical capacity (2980 mAh g^{-1}) [61]. Although the redox potential is much higher (-1,66 V *vs.* SHE) than that of lithium, aluminium still offers high overall energy density and significant safety and sustainability advantages. In contrast, zinc offers a practical balance between relatively high gravimetric (820 mAh g^{-1}) [62] and volumetric capacities (5585 mAh cm^{-3}) [63] with low production cost, significant abundance, and environmental compatibility. The highest reduction potential family (-0.78 V *vs.* SHE) [64], among multivalent families, makes it less reactive, thereby usable element for aqueous media. Nonetheless, commercialization of aluminium is still unable due to slow ion diffusion caused by charge to size ratio of the aluminum ion, and complex electrolyte chemistry required for reversible anode reaction [65,66].

Even though multivalent battery systems offer appealing theoretical performance (Figure 2), their commercialization remains limited to laboratory development. Recent advances in electrolyte design, including the development of weakly coordinating salts [46,67], usage of ionic liquids [68], deep eutectic solvents [69,70], polymer and solid-state electrolytes [71], have proven to effectively improve reversibility, efficiency and cyclability of multivalent metal anodes. Another approach to electrolyte design is the use of unstable solvents [72] or different kinds of additives that play a role in engineering the SEI layer, enabling reversible plating/stripping reactions. Moreover, utilization of the high-energy and power cathodes, such as sulphur [73] and oxygen [74], has been explored to further enhance energy and power density of multivalent batteries. These advances pave the way to unlocking the complete electrochemical capability of multivalent batteries.

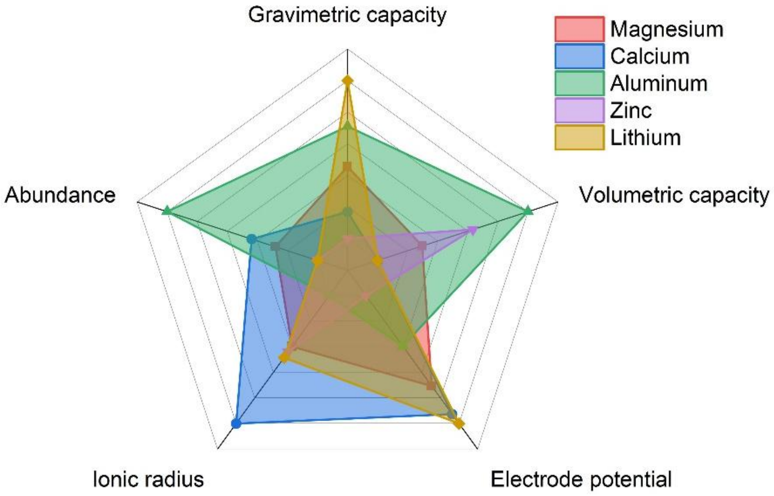

***Figure 2**. Radar plot for some multivalent battery systems*

Future perspective

Future battery development will focus on combining high performance with scalable, sustainable production. As demand, driven by electric vehicles, grid storage and portable electronics, increases, manufacturers will push toward chemistries that offer higher energy density, faster charging, longer cycle life and improved safety. Directions toward chemistries that minimize the dependence on geopolitical circumstances will be favoured. This will likely include advances in solid-state systems, silicon-rich and lithium-metal anodes, high-voltage cathodes, and cobalt-free or low-cobalt formulations. The future innovations are expected to enable more powerful batteries, but, at the same time, far easier and cleaner to manufacture at the terawatt-hour scale required for the energy transition.

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