2024

June

Recharge: New Battery Chemistries and Long-Term Energy Storage

Energy Research Paper

The Al-Attiyah Foundation

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Battery technologies are receiving intense attention and innovation, with new chemistries emerging that offer benefits over the conventional lithium-ion designs. These benefits span various aspects, including cost-effectiveness, reduced charging time, increased energy capacity, enhanced safety, and minimised use of scarce battery raw materials. The promising new chemistries include metal-ion batteries, metal-sulphur batteries, metal-air batteries and redox flow batteries.

In what ways are recent innovations influencing the development of alternative battery chemistries? Can alternative battery technologies be cheaper than lithium-ion batteries and where are the key applications? Are there alternative battery technologies that can significantly reduce dependencies on critical raw materials?

ENERGY RESEARCH PAPER

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Lithium-ion batteries have developed rapidly since their invention in the late 1970s, and now dominate key markets, particularly for consumer electronics, electric vehicles and electricity storage. Their cost and performance continue to improve. However, as further gains become more difficult, there is an intense search for alternative batteries that would avoid some of the problems or performance limits to lithium-ion.

- Alternatives to lithium-ion batteries and lithium intercalation in electrode materials can be developed through various chemistries, such as metal-ion, metal-sulphur, metal-air, and redox flow, which may use 1) alloys or conversion / deposition reactions at the electrodes, 2) entirely different electrode concepts, such as gaseous oxygen at the cathode, or 3) other charge-carrying elements or ions.

Alternative Battery Chemistries, Applications, and Costs:

- Initial costs related to alternative battery chemistries are expected to surpass those of lithium-ion batteries due to their limited production scales. Consequently, identifying substantial markets and utility-scale applications will be crucial for achieving economies of scale and reducing costs.

Technological Readiness and Global Players:

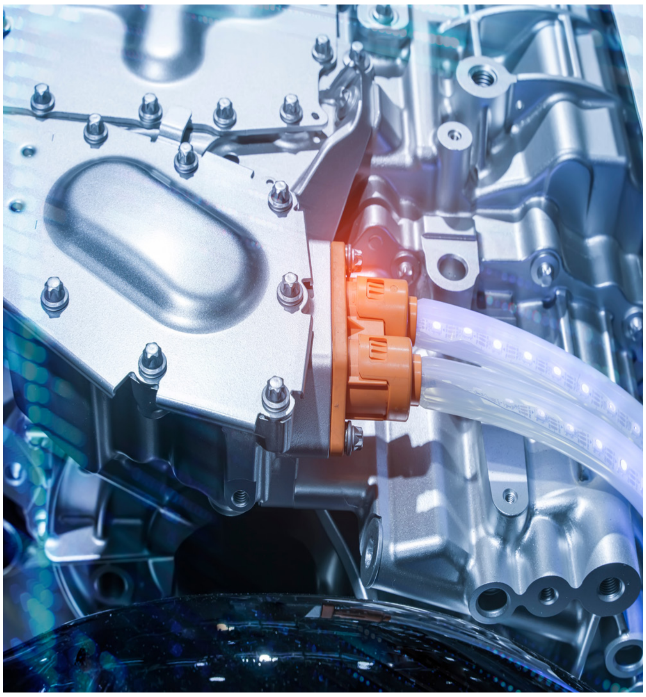
- Analyses of peer-reviewed publications show that Europe is better positioned for developing certain alternative battery chemistries, such as redox flow, lithium-air, and aluminium-ion batteries, in contrast to lithium-ion batteries. However, Japan and China continue to lead in overall battery technology patent applications and publication activities.

Raw Materials and Resource Dependency:

- Most non-lithium battery chemistries require fewer critical raw materials than lithium-ion batteries. However, without large-scale applications and offtake, the production and supply of lithium, nickel, and cobalt will remain critical, especially in the next 5 – 10 years. Most alternative battery chemistries have lower energy densities than lithium-ion, necessitating larger volumes of raw materials to achieve the same storage capacity.

Future of Alternative Battery Chemistries:

- Alternative battery technologies will for an extended period still compete with lithium-ion as the benchmark; therefore producers and developers must closely follow the production steps of alternative battery chemistries from components to cells, cell formats, and battery systems to potentially replace lithium-ion batteries in certain applications.



Lithium-ion batteries have developed rapidly since their invention in the late 1970s, and now dominate key markets, particularly for electric vehicles and electricity storage. Their cost and performance continue to improve. However, as further gains become more difficult, there is an intense search for alternative batteries that would avoid some of the problems or performance limits to lithium-ion.

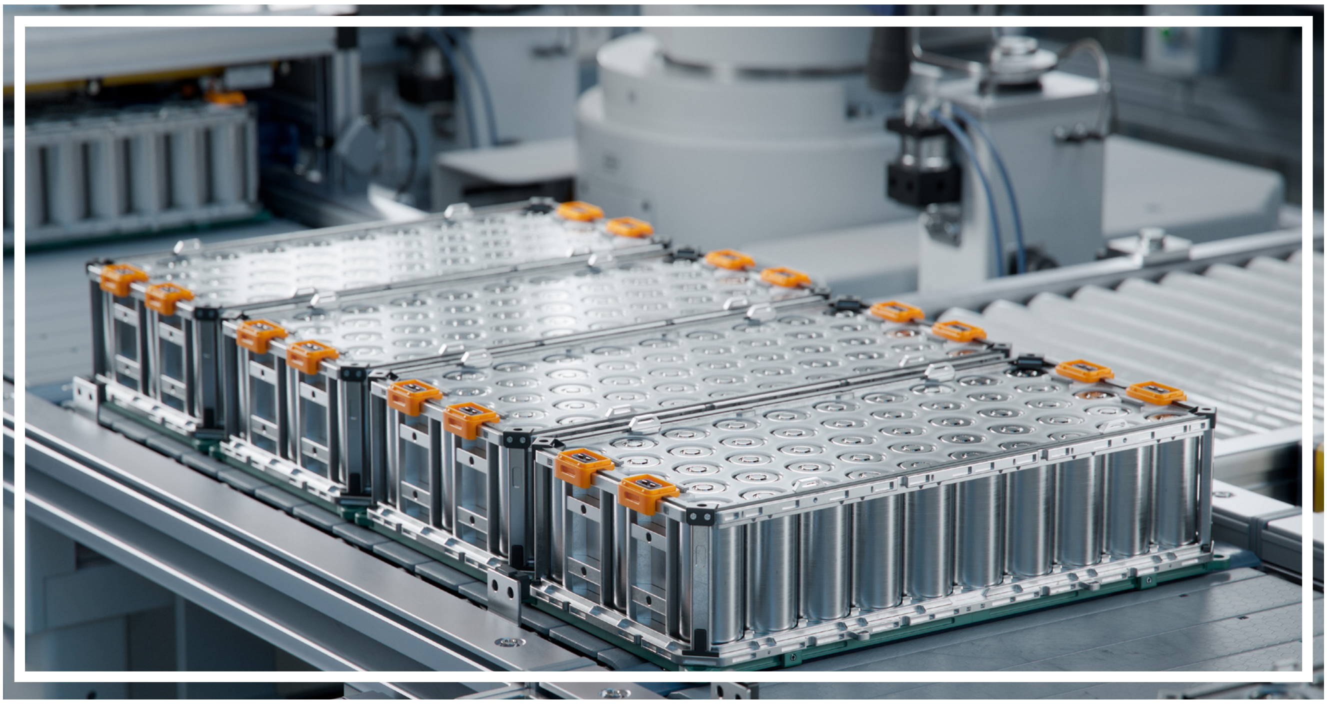
Lithium-ion batteries are currently the benchmark for a wide range of applications, including electrical consumer products, stationary storage systems, and e-mobility applications such as electric bikes, scooters, buses, trucks, and passenger cars. In the future, other battery technologies, such as solid-state batteries, might take over as the standard in certain applications. However, for now, emerging battery chemistries must compete with the well-established market of liquid electrolyte-based lithium-ion batteries.

The use of layered intercalated[1] materials, which serve as stable host structures for lithium-ions, creates a stable and high-performance electrochemical system. However, this results in high material overheads, limiting the energy density of lithium-ion batteries.

Lithium-ion batteries rely on the interfacial chemistry between electrodes and electrolytes[i]. Currently, liquid organic electrolytes are the only commercially viable option, but they are toxic, flammable, extremely water-sensitive, and difficult to recycle[ii].

1– Intercalation in batteries involves inserting foreign-ions or molecules between weakly-bonded layers.

Intercalation materials, which serve as stable structures for lithium-ions, create a stable and high-performance electrochemical system, but they result in high material overheads, limiting the energy density of lithium-ion batteries. Using silicon as an anode material is already a shift from conventional lithium-ion batteries towards lithium batteries. Despite this, further increases in energy density are unlikely with pure intercalated-ion chemistries.



Their manufacturing process involves critical steps that impact their emissions footprint, which includes the use of toxic solvents, the need for atmospheric conditioning to low dew points, and high energy consumption in material production, electrode fabrication, and cell formation[iii]. Despite new production systems being deployed to address these issues, many challenges are inherently linked to the characteristics of lithium-ion chemistries, limiting their production and optimal deployment.

Currently, the two most common lithium-ion battery chemistries are lithium-iron-phosphate (LFP) and lithium-nickel-manganese-cobalt oxide (NMC). NMC have higher energy densities than their LFP counterpart, resulting in better performance for deep cycle applications and superior acceleration for vehicles. However, LFP batteries excel in energy storage because of their lower cost, whereas NMC batteries offer stable performance, but have a shorter lifespan compared to LFP batteries.

LFP batteries are highly stable due to their chemical properties and structural framework. They do not catch fire or explode, even when punctured, compressed, or dropped from a height. In contrast, NMC batteries have a higher risk of fire and explosion, especially at high temperatures.

NMC batteries typically have a cycle life of 500 – 1,000 cycles, whereas LFP batteries can reach up to 5,000 cycles[iv]. LFP batteries can last more than 10 years on average, whereas most NMC batteries last only 2 – 3 years of heavy use (assuming 125,000 kilometre / year mileage)[v].

The rise in electric vehicle adoption is creating a new market for lithium batteries, still deciding on a preferred chemistry. The middle market segment is much more price-sensitive than the premium segment.

A variant of the NMC battery chemistry is lithium-nickel-manganese-cobalt-aluminium (NMCA), which includes aluminium in the intercalation, in order to enhance driving range, safety, and performance at reduced costs.

However, LFP battery deployment is currently leading NMCs in the electric vehicles industry because of its lower cost, a trend that could accelerate if lithium prices remain low. The market share of NMC batteries in the automotive industry is projected to decline from 51% in 2022 to 42% by 2030, the market share for LFP batteries is estimated to increase from 38% in 2022 to 41% by 2030, and NMCA batteries are projected to increase from 4% in 2022 to 8% by 2030[vi]. Motorists in China appear more willing to accept LFP, while US drivers demand the longer ranges obtainable with NMC.

Battery metal prices are expected to continue declining in 2024. Advancements in cathode and anode chemistries, new battery pack geometries, and improved cell manufacturing processes will be crucial for further cost reductions by 2030.

Lithium, although present in small proportions (by weight) in lithium-ion batteries, significantly contributes to the overall cost and emissions intensity of lithium batteries. The availability of lithium in sufficient quantities is still debated. Recycling lithium can help alleviate this problem, but the large, required scale-up of batteries for electric vehicles and grid storage mean that substantial amounts of recycled lithium will only become available when the first major generations of this equipment reach the end of their useful lives, in a decade or more.

High demand and supply shortages have caused lithium prices to skyrocket over the past two years, a trend also seen with other important precursor materials like cobalt and nickel sulphate, which has driven up the price of cathode active materials, which is the largest cost component of lithium-ion batteries[vii]. Additionally, energy, labour, research and development, and depreciation costs have also contributed to the rising production costs. Even though lithium prices have fallen sharply in 2024[viii], volatility may deter investment in new production, and makes planning difficult. New cycles of high prices and tight supply are likely.

Energy costs increased in many lithium-ion battery producing countries, particularly in 2022[ix]. Investment costs for production equipment have also risen due to high demand and the scale-up of new gigafactories. Consequently, the price of battery-electric grade lithium-ion cells increased from US$ 100 / kWh in 2021 to US$ 120 / kWh in 2022.[x] However, in 2023, price of lithium-ion battery packs has declined by 14% y-o-y to a record low of US$ 139 / kWh, driven by falling raw material and component prices, as production capacity increased across all parts of the battery value chain[xi].

Still, earlier cost targets for lithium-ion batteries of less than US$ 80 – 86 / kWh for this decade now seem distant[xii]. If high prices continue to strain lithium-ion batteries, including the most efficient ones, cheaper alternative battery chemistries may become more favourable.

As battery prices fall, the electric vehicle market could achieve cost parity with internal combustion engine vehicles on a total-cost-of-ownership basis between 2025 – 2030 (possibly without subsidies)[xiii]. It has been thought this would be achieved at a battery price of <$100 / kWh. However, this depends on other performance characteristics of the batteries (charging rates, lifetime) and on consumer preferences (particularly the desired vehicle range). The reduction in battery costs could lead to more price-competitive electric vehicles, extensive consumer adoption, and further growth in the total addressable market for batteries in the electric vehicle production. Initially driven by regulatory support schemes, the electric vehicle industry is now seeing a retreat in global penetration from recent highs, potentially due to reduced subsidies from governments in Europe and China.

Alternatives to lithium-ion batteries and lithium use in electrode materials can be developed through various chemistries, such as metal-ion, metal-sulphur, metal-air, and redox flow. These alternatives either use 1) alloys or conversion / deposition reactions at the electrodes, 2) entirely different electrode concepts, such as gaseous oxygen at the cathode, or 3) other charge-carrying elements or ions.

Many alternatives to lithium have either a less favourable electrode potential or a larger ionic radius. Whilst these parameters do not directly describe battery performance, they indicate the achievable cell voltage and the required storage volume.

Despite these challenges, alternative battery systems could be highly suitable for specific applications. Technical solutions must be developed at all levels and lifecycle stages of a battery, including suitable active materials and electrolytes with high kinetics and stability, scalable manufacturing processes, and strategies for handling batteries at the end of their life.

Metal-ion chemistries convert and store electrochemical energy by shuttling a single type of ion between the negative and positive electrodes during discharging and charging.

These batteries typically feature a specific cathode and anode material, each placed on a metallic current collector foil, separated by a microporous separator, with ion transport facilitated by a liquid electrolyte[xv]. Whilst lithium-ion is the most well-known metal-ion used in batteries, other metals like sodium, aluminium, zinc, and magnesium can also be used[xvi].

Figure 1: Technological Readiness, Market Development, Raw Materials Dependency, and Costs for Alternative Battery Chemistries

Alternative Battery Technology	Battery Chemistry	Technological Readiness, 2023	Market Development and Applications in Comparison to Lithium-ion Batteries	Raw Materials and Resource Dependency in Comparison to Lithium-ion Batteries	Potential Long-Term Cell Costs Reductions in Comparison to Lithium-ion Batteries
			Note: a full circle denotes high market development, substantially better raw materials / resource dependency, and greater long-term cell cost competitiveness than lithium-ion batteries		
Metal-ion Batteries	Sodium-ion	8 – 9	¾	¾	⅝
	Sodium-ion Saltwater				
	Magnesium-ion				
	Zinc-ion	3 – 4	¼		¾
	Aluminium-ion		¾		⅝
Metal-Sulphur Batteries	Lithium Sulphur	5 – 7	½	⅝	
	Sodium Sulphur (Room Temperature)	4	¼		
	Sodium Sulphur (High Temperature)	9			
Metal-Air Batteries	Lithium-air	2 – 3		½	⅝
	Zinc-air	2 – 4		⅝	
Redox Flow Batteries	Vanadium Flow	9		⅝	¾

Researchers are actively studying and developing metal-sulphur chemistries due to the favourable properties of sulphur as a cathode active material. Sulphur is abundant, cost-effective, and lightweight. Various metals are investigated in combination with a sulphur cathode, including lithium, sodium, potassium, magnesium, calcium, and aluminium. These metals, being more plentiful than lithium, are also of significant interest for metal-sulphur batteries. Among these systems, lithium sulphur demonstrates the most advanced operational stability at room temperature[xvii].

Metal-air chemistries consist of lithium or zinc-based electrodes, an electrolyte, and a gas diffusion electrode, which supplies the active oxygen component from the surrounding air or an oxygen tank[xviii]. Metal-air chemistries offer high theoretical energy density and potential low cost, but face significant challenges in stable operation, cycle life, and efficiency[xix].

Redox flow chemistries involve two electrolyte tanks storing electrical energy as redox couples, typically in an aqueous solution[xx]. A battery cell converts electrical energy into chemical energy and vice versa as the electrolytes are pumped through it. The major advantage is that the storage capacity is determined by the size of a tank of inexpensive, stable chemicals, and extra storage capacity can therefore be added at low cost.

The weight and volume are high, making this more suitable for stationary applications such as grid storage. Various chemical redox systems exist for redox flow chemistries, with vanadium being the most commercially mature, but relatively expensive[xxi].

Initial costs associated with alternative battery chemistries are anticipated to exceed those of lithium-ion batteries due to limited production scales. Consequently, identifying sizable markets and utility-scale applications will play a critical role in achieving economies of scale and cost reduction.

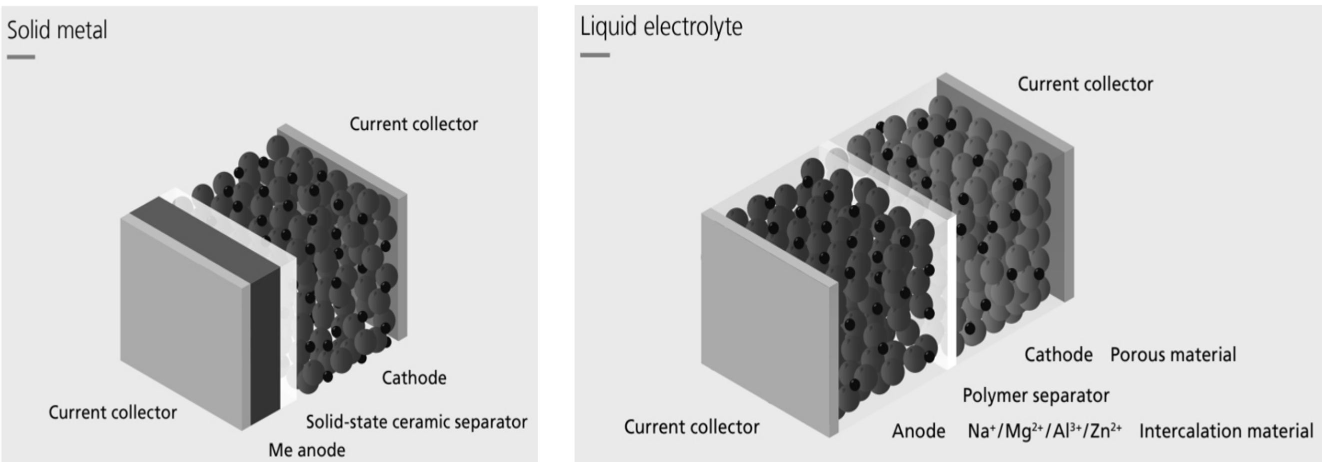
Recent discussions on resource availability, emissions intensity, and cost reduction relating to metal-ion chemistries highlight the need for alternative battery chemistries to meet specific application requirements and reduce material dependencies. These alternatives complement rather than replace lithium-ion batteries, offering unique strengths for various applications. For instance, sodium-ion batteries are ideal for stationary applications or light electric vehicles, whereas aluminium-ion batteries can replace lithium-titanate-oxide-based lithium-ion batteries given their high power densities.

Sodium-ion batteries are a cost-effective and sustainable alternative to lithium-ion batteries. Although their energy density is generally lower than NMC cells, they could eventually replace LFP and lead-acid batteries[xxii]. These batteries use a sodium-containing cathode and a carbon-based anode, typically with a liquid electrolyte[xxiii].

Sodium is much more abundant than lithium, with concentrations of 28,400 milligram / kilogramme in the earth's crust and 11,000 mg / L in water, compared to lithium's 20 milligram / kilogramme and 0.18 milligram / litre[xxiv]. Sodium-ion batteries have lower material costs than lithium-ion batteries, not just in replacing lithium but particularly on the cathode side, by avoiding expensive raw materials like cobalt and possibly nickel.

Using aluminium instead of cobalt for the anode current collector can also be more economical[xxv]. However, the higher cost of hard carbon compared to graphite is a drawback, as its lower specific density and higher irreversible capacity require a thicker coating and more active material[xxvi]. Overall, the material costs of sodium-ion battery cells are estimated to be 40% - 60% of those for lithium-ion cells, depending on the material pairing[xxvii].

Figure 2: Typical Intercalation (Liquid Electrolyte and Solid Metal) of a Metal-ion Battery (i.e. Lithium, Sodium, Magnesium, Aluminium, and Zinc-ion)



Magnesium-ion batteries offer high theoretical capacity and exceptional safety due to their high temperature and dendrite[2] growth resistance[xxviii]. Magnesium-ion batteries are intercalated similarly to sodium-ion and lithium-ion batteries but use metallic magnesium for the anode. The high reactivity of magnesium metal causes dendrites to be almost instantly passivated in the electrolyte, which results in higher intrinsic resistance of the dendrites compared to pure magnesium metal[xxix].

The earth's crust contains 1,000 times more magnesium than lithium[xxx]. Abundant materials for high-voltage cathodes eliminate depletion risks and support robust supply chains for the future battery industry. Consequently, magnesium costs roughly are a third of lithium – this cost differential is expected to increase as demand for lithium outpaces supply[xxxi]. Therefore, the raw material cost for magnesium-ion batteries could be even lower in the long-term compared to current lithium-ion batteries.

Zinc-ion batteries provide a safer alternative to lithium-ion batteries, since they utilise low-cost aqueous electrolytes that are non-flammable. Like magnesium-ion batteries, zinc-ion batteries benefit from abundant zinc deposits.

Due to its high availability, zinc costs are significantly less at US $2.6 / kilogram compared to the current annual average lithium price of US$ 300 – 350 / kg[xxxii]. Similarly, manganese, a component of potential manganese-oxide cathode materials, is priced below US$ 2 / kg[xxxiii]. Other cathode materials based on vanadium or cobalt tend to be more expensive.

2- Dendrites are projections of a metal that can build up on a metal surface (usually due to accumulation of solute and / or high heat) and penetrate into the solid electrolyte, eventually crossing from one electrode to the other and shorting-out the battery cell.

Figure 3: Projected Long-Term Key Performance Indicators for Selected Metal-ion Chemistries

Alternative Battery Chemistry	Sodium-ion	Sodium-ion Saltwater	Magnesium-ion	Zinc-ion	Aluminium-ion
Volumetric Energy Density	> 300 Wh / l	100 Wh / l	400 – 750 Wh / l	80 – 200 Wh / l	520 – 616 kWh / l (for carbon-based), 45 – 8 Wh / l (for cell-based)
Power Density	> 300 W / kg	-	Greater than lithium-ion batteries	30 – 150 W / kg	> 10,000 W / kg
Cycle Life	500 – 4,000 cycles	> 10,000 cycles	> 1,000 cycles	300 – 3,000 cycles	> 50,000 cycles
Calendar Life	> 15 years	> 10 years	Similar to lithium-ion batteries	-	Several months
Energy Efficiency	> 95%	> 98%	-	80% - 90%	70% - 90%

Additionally, components like the aqueous electrolyte are substantially cheaper compared to their organic lithium-ion battery counterparts. Zinc batteries could cost less than US$ 45 / kWh in the long-term[xxxiv].

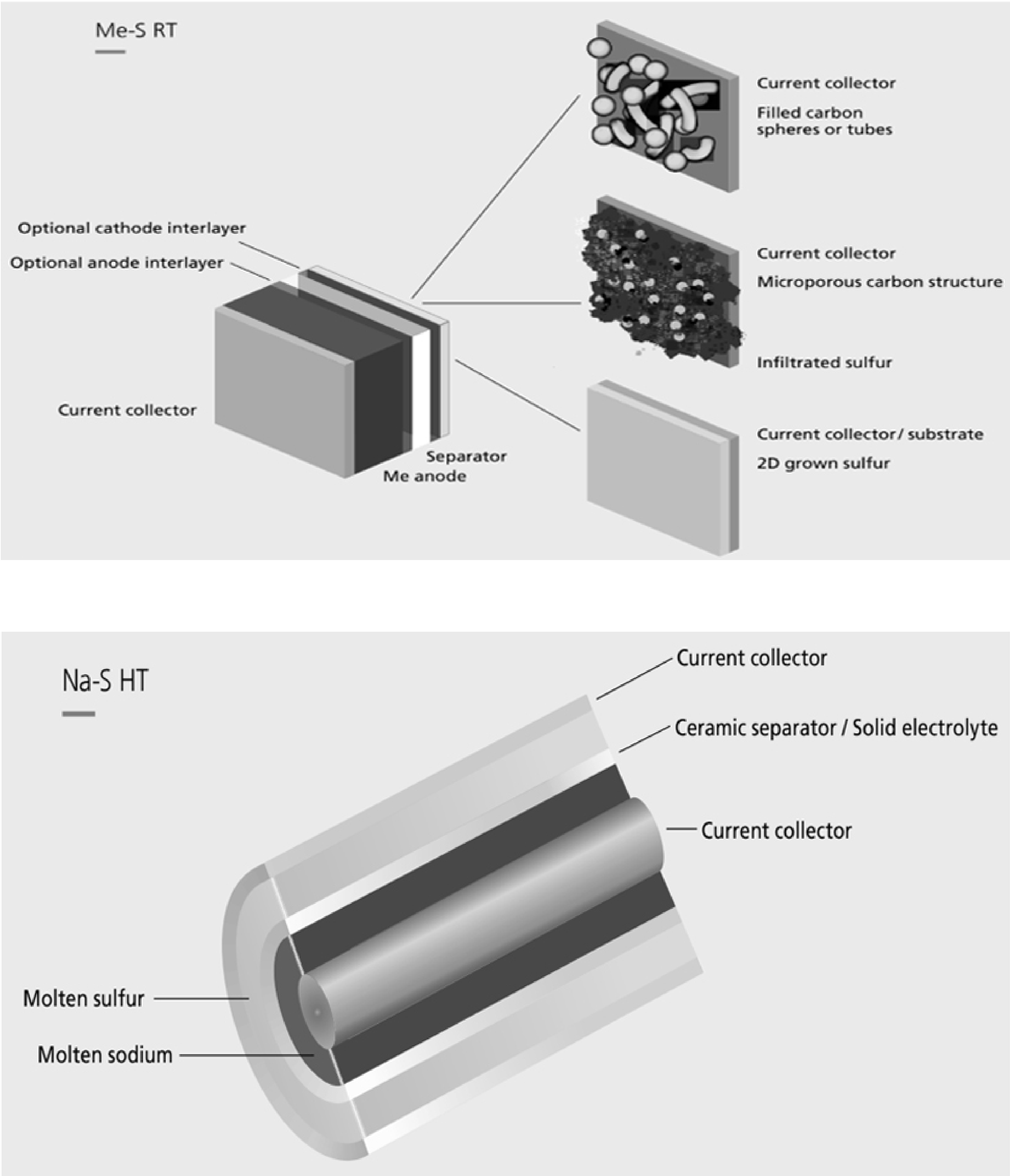
Aluminium-ion batteries stand out across all metal-ion chemistries due to aluminium's ability to donate three electrons, enabling high power density, fast charge rates, and long cycle life. These batteries feature aluminium metal in the anode.

In the long-term, fully developed aluminium-ion batteries could deliver cost savings of ~10% – 20% compared to current lithium-ion batteries[xxxv]. When compared to lithium-titanate-oxide-based lithium-ion batteries, the cost advantage will likely be even greater due to the use of cheaper materials and the elimination of manufacturing steps, such as avoiding coating processes on the anode side. Although it's possible to produce aluminium-ion batteries on existing lithium-ion battery production lines, maintaining low humidity during production will be crucial.

There is growing interest in fully organic metal-ion batteries, such as organic lithium-ion and sodium-ion batteries, which promise high resource availability, low costs, and a low emissions intensity. However, challenges like low electronic conductivity and high solubility of organic electrode materials in the electrolyte mean that the technological readiness of organic batteries remains low.

Sulphur in metal-sulphur chemistries can react with lithium, sodium, magnesium, and other metals to form metal sulphites, making it a promising, low-cost, and abundant cathode material[xxxvi].

Figure 4: Typical Structure of a Metal-Sulphur Battery (Room and High Temperature)



Battery cells with metallic lithium or sodium anodes promise high energy densities. Further advancements in cell components such as electrolytes, membranes, and specialised carbons will be essential for their future commercialisation[xxxvii].

Lithium sulphur batteries are the most operationally stable metal-sulphur chemistry at room temperature, and can be cheaper than lithium-ion batteries from a raw materials cost perspective given the low cost of sulphur.

However, achieving this cost advantage requires overcoming several challenges, which include developing and scaling up a cost-efficient process for thin lithium metal anodes, reducing the amount of electrolyte, and increasing sulphur loading in the cathode while using a low-cost carbon matrix. Successfully addressing these challenges could bring lithium-sulphur batteries to cost parity with lithium-ion batteries. In the long-term, depending on how lithium prices evolve, lithium sulphur cell costs of < US$ 45 / kWh might be attainable[xxxviii].

Although sodium sulphur room temperature batteries lag significantly behind lithium sulphur batteries in terms of technological maturity, they offer an intriguing alternative within the metal sulphur chemistry class. The key advantage lies in substituting resource-critical lithium with sodium. These batteries provide a storage solution that is nearly devoid of high cost raw materials and has the potential for cost effective production. Whilst sodium sulphur high temperature batteries have already achieved some commercial success, their room temperature counterparts remain in the research phase, and no commercially viable deployments have been established thus far.

Figure 5: Projected Long-Term Key Performance Indicators for Selected Metal-Sulphur Chemistries

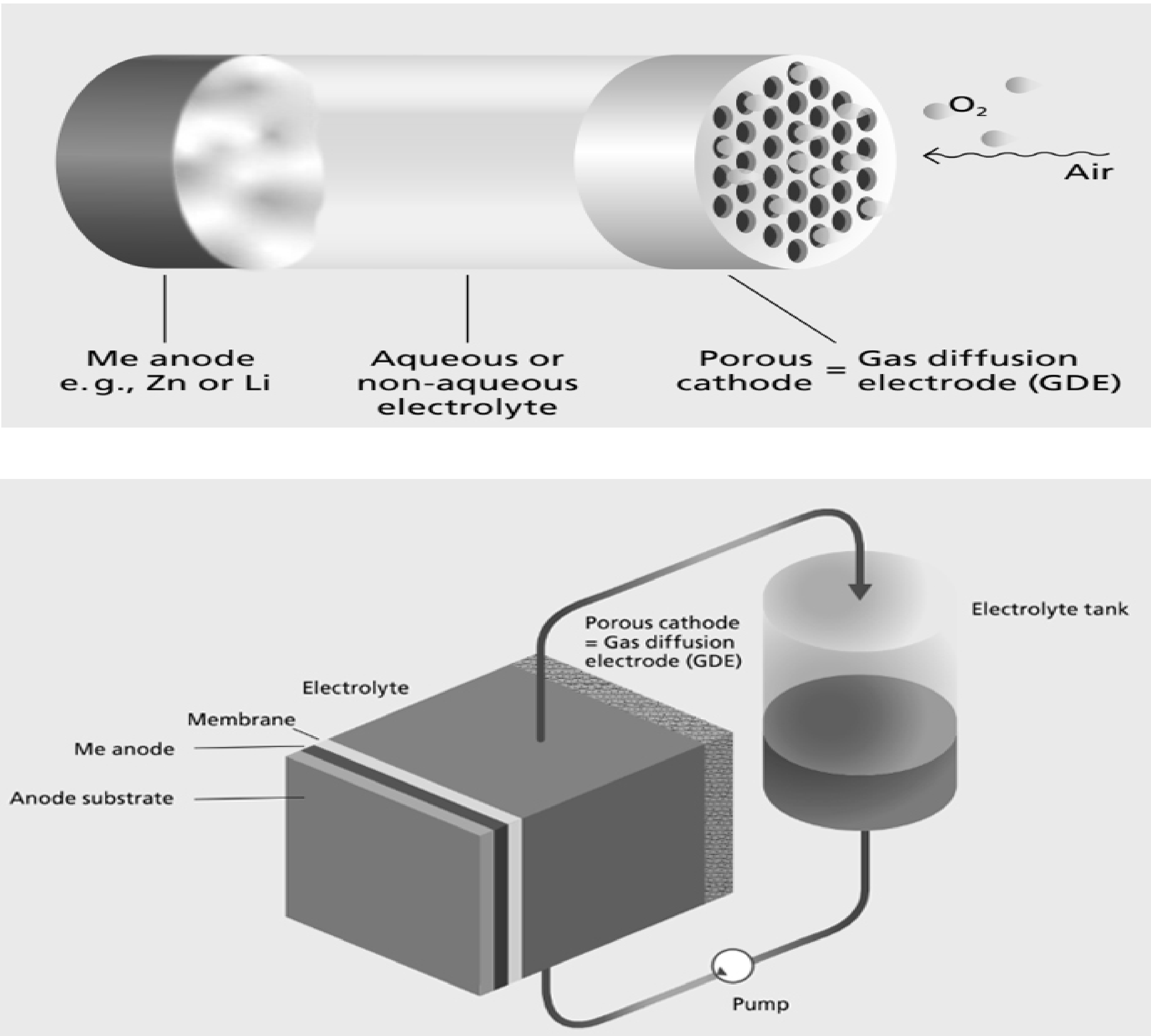
Alternative Battery Chemistry	Lithium Sulphur	Sodium Sulphur (Room Temperature)	Sodium Sulphur (High Temperature)
Volumetric Energy Density	> 700 Wh / l	-	400 Wh / l
Power Density	< 500 W / kg	-	-
Cycle Life	> 500 cycles	> 500 cycles	> 7,000 cycles
Calendar Life		-	-
Energy Efficiency	85%	> 70%	> 80%

Metal-air chemistries use lithium or zinc-based electrodes, an electrolyte, and a gas diffusion electrode to supply oxygen from the air or an oxygen tank.

Metal-air chemistries offer a significant advantage over lithium-ion batteries due to their theoretically high energy density and potential cost-effectiveness. The cost savings stems from their high energy density, material efficiency, and the use of less expensive cathode materials. However, non-aqueous metal-air batteries tend to be more costly than their aqueous counterparts due to higher electrolyte expenses.

Challenges remain, including poor cycling capability and low energy efficiency. However, metal-air chemistries are considered environmentally friendly, particularly in

Figure 6: Typical Structure of a Metal-Air Battery (Open Cell Design and Flow Cell Design)



aqueous designs and serve as a competitive option for stationary storage systems. Lithium and zinc are the most commonly used materials in metal-air batteries, in comparison to calcium, sodium, aluminium, magnesium, iron, and potassium; lithium and zinc.

Lithium-air batteries are anticipated to have lower cell costs compared to lithium-ion batteries due to material savings and the utilisation of less expensive materials, including graphite[xxxix]. However, lithium-air batteries still rely on lithium, which remains one of the costlier components. Additionally, due to their low technological readiness, cost estimates for lithium-air batteries remain highly uncertain, with potential pack prices estimated to fall within US$ 70 - 200 / kWh[xl].

Although zinc-air batteries have been commercially available for several years, there is still a lack of rechargeable zinc-air batteries with good overall performance. Zinc prices are substantially lower than those for lithium carbonate. Since zinc is the only active material, the chemical cost of storage is ~US$ 6 / kWh, which is seven times lower than that for lithium-air batteries[xli].
Manufacturing costs for zinc-air batteries are not yet known as the technology still has to improve its technological readiness to mass production, which could push total costs below US$ 100 / kWh in the long-term[xlii].

Vanadium redox flow batteries stand out as the most mature redox flow chemistry and are already commercially available at a technological readiness level of 9. These batteries comprise of two electrolyte tanks where redox couples are stored, a battery cell responsible for energy conversion containing electrodes and a separating membrane, and pumps to circulate the electrolytes through the battery cell[xliii].

Vanadium redox flow batteries incur vanadium pentoxide as their primary cost driver, with prices ranging from US$ 15 – 20 / kg[xliv]. Whilst vanadium is not a rare element, relying on imports could create dependencies on the main producing countries, China, Russia, South Africa, and Brazil.

Figure 7: Projected Long-Term Key Performance Indicators for Selected Metal-Air Chemistries

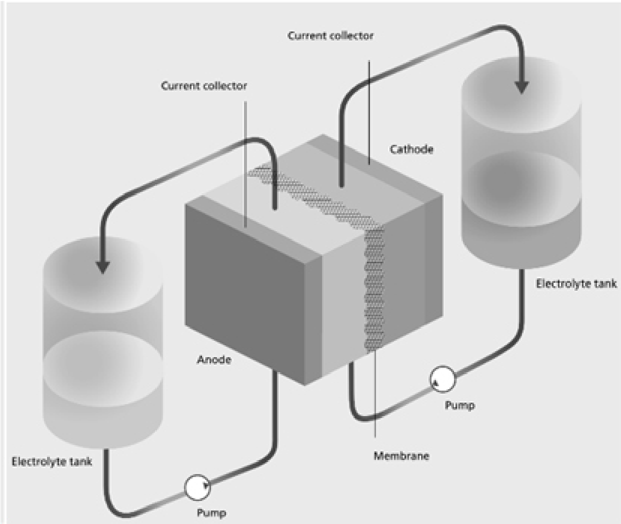
Alternative Battery Chemistry	Lithium-Air	Zinc-Air
Volumetric Energy Density	> 700 Wh / l	-
Power Density	Less than lithium-ion batteries	Less than lithium-ion batteries
Cycle Life	-	100 – 2,000 (for zinc-air) and 10,000 – 14,000 (for zinc-air flow)
Calendar Life	-	Low (for zinc-air) and 25 years (for zinc-air flow)

Figure 9: Projected Long-Term Key Performance Indicators for Vanadium Redox Flow Batteries

Alternative Battery Chemistry	Vanadium Redox Flow
Volumetric Energy Density	> 50 Wh / l
Power Density	Scalable
Cycle Life	> 1,000 cycles
Calendar Life	15 – 20 years
Energy Efficiency	-

Consequently, research is underway on exploring alternative redox flow chemistries, including zinc, iron, and organic materials, which may offer lower costs and greater material availability.

Figure 8: Typical Structure of a Vanadium-Redox Flow Battery



Non-lithium battery chemistries use fewer critical raw materials compared to lithium-ion batteries. However, without large-scale applications and offtake, the production and supply of lithium, nickel, and cobalt will remain crucial, particularly over the next 5 – 10 years. Most alternative battery chemistries have lower energy densities than lithium-ion, requiring larger volumes of raw materials to achieve the same storage capacity.

The production of lithium-ion batteries requires a variety of materials, starting with ores. The cathode material, due to its high weight, significantly contributes to the material intensity. Transition metal-based cathode active materials necessitate the extraction of compounds like magnesium, iron, cobalt, or nickel from ores, and lithium salts from salars or ores. Passive components such as copper or aluminium collectors and casings made of aluminium or steel also add to the material demand for these batteries.

The solvents for the electrolyte and separator foils are petrochemical products. The anode material, graphite, can be mined or synthetically produced from petrochemical precursors.

Lithium is essential for lithium-ion batteries, regardless of the cell chemistry. Depending on the cathode material, the storage capacity of current lithium-ion batteries is 4 kWh / kilogramme, and with annual battery demand, soon to be in the terawatt range, lithium-ion batteries will require tens to hundreds of kilotons of lithium / year[xlv].

Lithium has the been the preferred charge-carrying element in batteries due to its low weight and the high voltage of many cathode materials. Recently, sodium-ion batteries have shown a storage capacity of 2 - 5 kWh / kg[xlvi], whilst zinc-ion batteries have around 1 kWh / kg[xlvii].

Figure 10: Mined Production and Reserves of Selected Metals and Materials used in Lithium-ion and Alternative Battery Chemistries, 2023

Selected Material / Metals	Global Mined Production (in kilo-tonnes), 2023	Global Reserves (in million tonnes), 2023
Aluminium	70,000	30,000
Bromine	> 400	Large
Calcium	-	Large
Cobalt	190	8
Copper	26,000	890
Iron	1,600,000	85,000
Graphite	1,300	330
Potassium	40,000	3,000
Lithium	130	26
Magnesium	27,000	6,800
Manganese	20,000	1,700
Sodium	> 290,000	Large
Nickel	3,300	> 100
Lead	4,500	85
Phosphorus	220,000	72,000
Sulphur	82,000	Large
Vanadium	100	26
Zinc	13,000	210

The geographical distribution of lithium and other raw materials used in non-lithium battery chemistries will significantly impact the commercial viability of these materials. The GCC is not a major producer of these materials, but it does have access to global supply chains and the necessary expertise in indigenous production, including notable reserves of copper, silicon, zinc, nickel, iron ore, phosphates, and potassium ore in Saudi Arabia and Oman.

The largest global lithium producers are in Australia, Chile, and China, with the latter holding the single-largest global lithium processing and refining capacity. Cobalt production is mainly concentrated in the Democratic Republic of Congo. Nickel production is much more geographically varied, with major mining sites across the Asia-Pacific region, particularly Indonesia, the Philippines and New Caledonia. Manganese and iron are less critical and widely mined globally, with small accessible deposits in the GCC. Natural graphite (used in anode active materials) deposits are also globally distributed, but not all grades are suitable for lithium-ion batteries. Synthetic graphite refining and processing, with heavy crude oil as a precursor, is mainly concentrated in China.

Raw material distribution looks very different for the charge-carrying elements used in alternative battery technologies, but also for the materials used in anodes and cathodes. Germany and the Netherlands are among the top ten producers of common salt and sodium. The largest aluminium smelters are in China; however Emirates Global Aluminium, Aluminium Bahrain and Qatar Aluminium provide a significant proportion of global supply, alongside non-Chinese producers such as Rio Tinto and Norsk Hydro.

Analyses of peer-reviewed publications reveal that Europe is better positioned to develop alternative battery chemistries like redox flow, lithium-air, and aluminium-ion batteries. However, Japan and China continue to dominate in overall battery technology patent applications and publications.

The number of peer-reviewed publications on lithium-ion batteries increased exponentially between 2008 – 2014, with the total number of publications increasing by 1,500 to 2000 publications by the end of 2010. Since then, ~1,000 additional articles have been published annually (see figure 7).

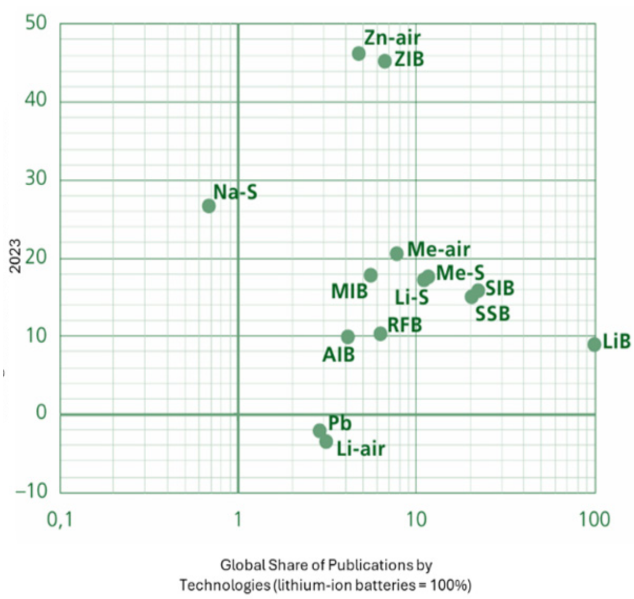
In contrast, alternative battery chemistries have developed since 2012, starting from a few percent and increasing to 10% - 20%, with most publications focusing on sodium-ion and lithium sulphur batteries. Publications on zinc-ion and zinc-air batteries have grown significantly. Publications on redox flow batteries increased at similar growth trajectory to lithium-ion batteries, whereas sodium sulphur batteries have higher growth rates but have a global of < 1%. Peer-reviewed publications on lithium-air batteries are currently declining.

China leads in all alternative battery technologies, holding 30% - 80% of global peer-reviewed publications, depending on the alterative battery chemistry and in terms of lithium-ion batteries, China holds a 55% share (see figure 8). The Chinese Academy of Sciences and numerous leading universities drive these publication activities, both domestically and through global cooperation.

In the United States, universities and research institutions contribute 10% - 25% of global peer-reviewed publications, depending on the battery technology.

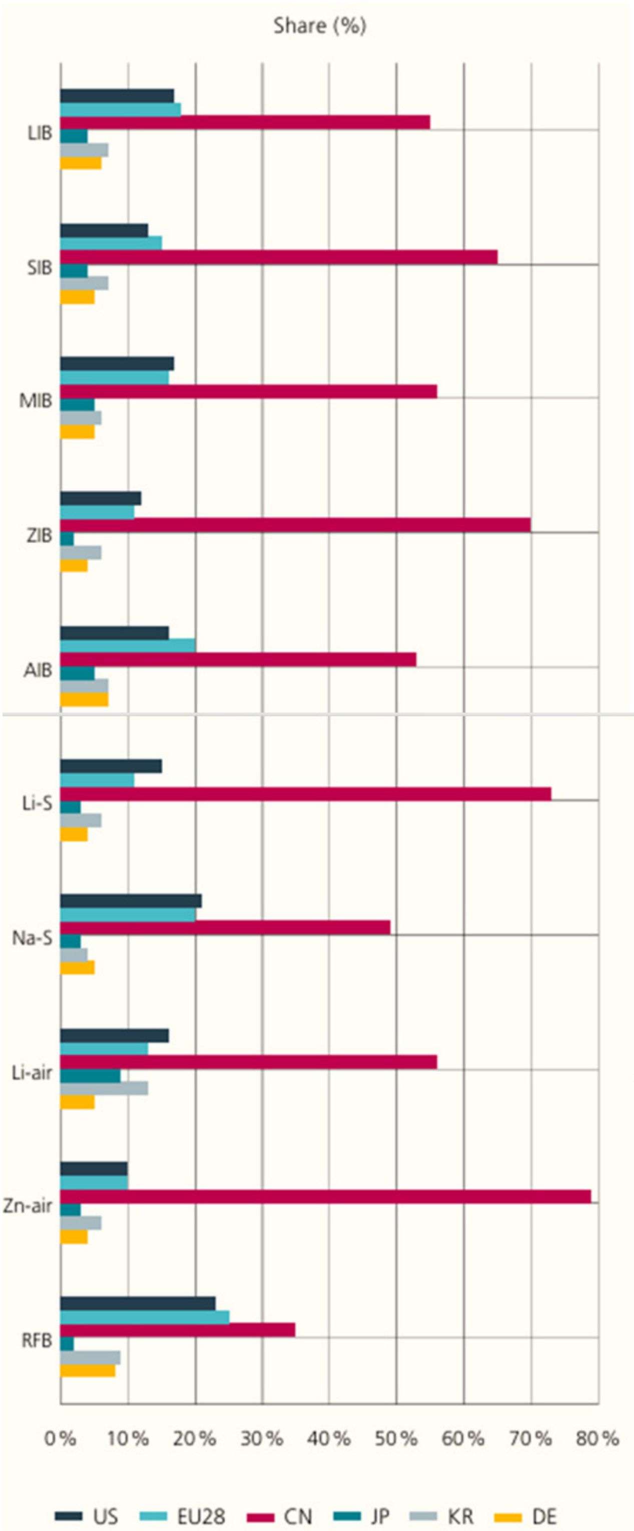
Europe has a similar share, with research centres at the Karlsruhe Institute of Technology and FZ Jülich in Germany, and the Centre National de la Recherche Scientifique in France, along with top universities, being key contributors. In Japan and South Korea, leading universities and research institutes contribute 5% - 10% of publications.

Figure 11: Global Share of Peer-Reviewed Publications by Alternative Battery Chemistries



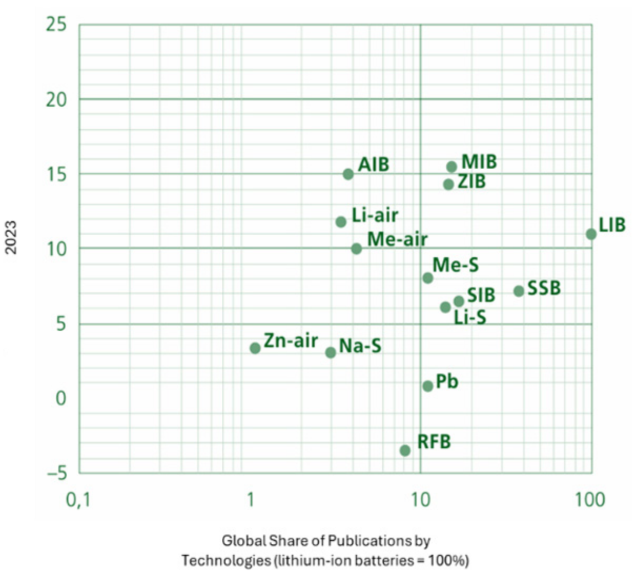
Moreover, the number of patent applications for lithium-ion batteries increased from 200 to 1,000 between 2000 – 2010, peaking at around 1,600 applications in 2012. In comparison, sodium sulphur battery patent applications have a much smaller share and growth rate. However, research on high-temperature sodium sulphur batteries has advanced faster than that on room-temperature sodium sulphur batteries, which are still in their early stages of technological readiness.

Figure 12: Global Share of Peer-Reviewed Publications by Alternative Battery Chemistries by Country and Region



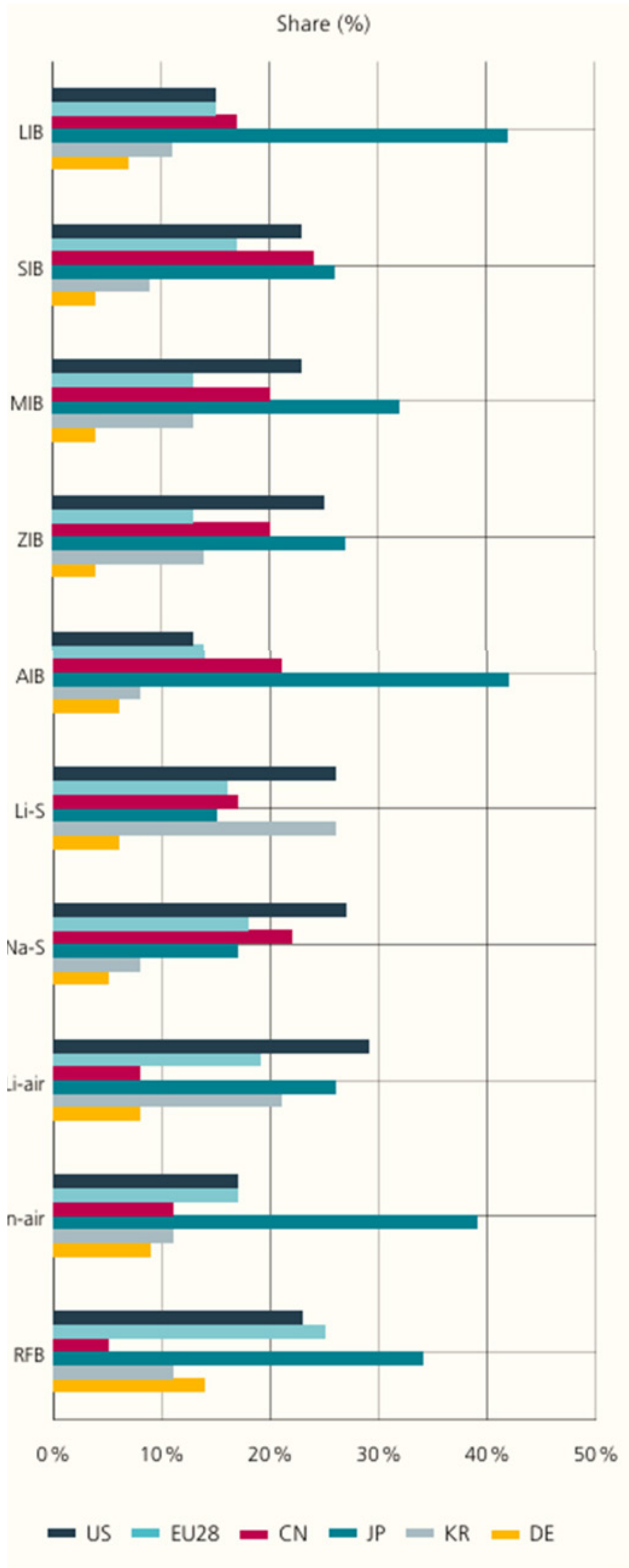
Globally, zinc-air batteries account for 1% of global patent applications, whereas lithium-air and aluminium-ion batteries collectively hold 10%. Redox flow batteries also have a 10% share (see figure 9). Lithium sulphur, magnesium-ion, zinc-ion, and sodium-ion batteries each have less than 10%. Solid-state batteries have a significantly higher share, reaching up to 40% compared to recent lithium battery patent applications.

Figure 13: Global Share of Patent Applications by Alternative Battery Chemistries



Japan leads in all battery chemistries, holding a global share of patent applications between 25% - 40% (see figure 10). It also has the highest global share of patent applications for lithium-ion and aluminium-ion batteries at 42%. However, the United States and South Korea surpass Japan in lithium sulphur battery patents, each holding a 25% share. For lithium-air batteries, the United States leads with a 30% share.

Figure 14: Global Share of Patent Applications by Alternative Battery Chemistries by Country and Region



For lithium-ion batteries, China, the United States, and Europe each hold global shares between 15% - 17% (see figure 10). South Korea, with an 11% share, and Germany, with a 7% share, remain among the top five countries, though their growth rates are below 10%. Other countries collectively hold a 5% share in global lithium-ion battery patent applications, with a high growth rate of 70%.

In Japan, leading cell manufacturers, such as Panasonic and GS Yuasa, along with various suppliers, are driving patent activities. In South Korea, cell manufacturers such as LG, SDI, and SK are the top patent applicants. In China, companies like CATL and BYD are leading patent applications.

In the United States, applicants range from material suppliers to battery integrators, including universities and research institutions. In Europe, large companies along the battery value chain, especially material and chemistry companies like BASF and Umicore, as well as OEMs (Original Equipment Manufacturers), are the leading patent applicants. In some cases, cell manufacturers and research organisations, and less frequently universities, also contribute.

Alternative battery technologies will compete with lithium-ion for an extended period as the benchmark; therefore producers and developers must closely follow the production steps of alternative battery chemistries from components to cells, cell formats, and battery systems to potentially replace lithium-ion batteries in certain applications.

Almost every major electric vehicle manufacturer has a commitment to LFP or NMC batteries in the medium-term, and it is likely that only a select group of alternative battery technologies will be adopted in the electric vehicle market in the long-term. If alternative battery chemistries achieve key performance indicators comparable to today's lithium-ion batteries, they could address a potential market in the double-to-triple digit gigawatt-scale.

For premium electric vehicles, alternative battery technologies with significant improvements in energy density and charging speed could play an important role. Although customers in this segment are less price-sensitive and constitute only a small share of the total electric vehicle market, they can act as a bridge to scale-up and wider adoption.

Regarding commercial electric vehicles, alternative battery chemistries may reduce product costs or extend operational lifetimes. Whilst similar developments are expected for light commercial electric vehicles, alterative batteries deployment in heavy-duty vehicles will continue to compete with traditional internal combustion engines or fuel cells in the short-to-medium term.

Alternative battery technologies could also serve new applications in battery-electric aircraft, space applications, ships, or trains. Short-range electric aviation is a market where high energy density will be more important than battery cost.

In the medium-term, a megawatt-scale market is plausible; however if they prove commercially feasible, gigawatt-scale markets could emerge in the long-term.

For energy storage systems, batteries with high cycle stability or high power are increasingly taking precedence over energy density. Consequently, alternative battery chemistries that address these requirements may be more favourable than lithium-ion batteries.

In the short-term, lithium-ion batteries will continue to replace lead-acid batteries in the residential sector. It is unlikely that alternative battery technologies will replace lithium-ion batteries in this sector anytime soon. Hence, residential home storage systems are likely incorporate only a small megawatt-scale deployment of alternatives in the short-to-medium term.

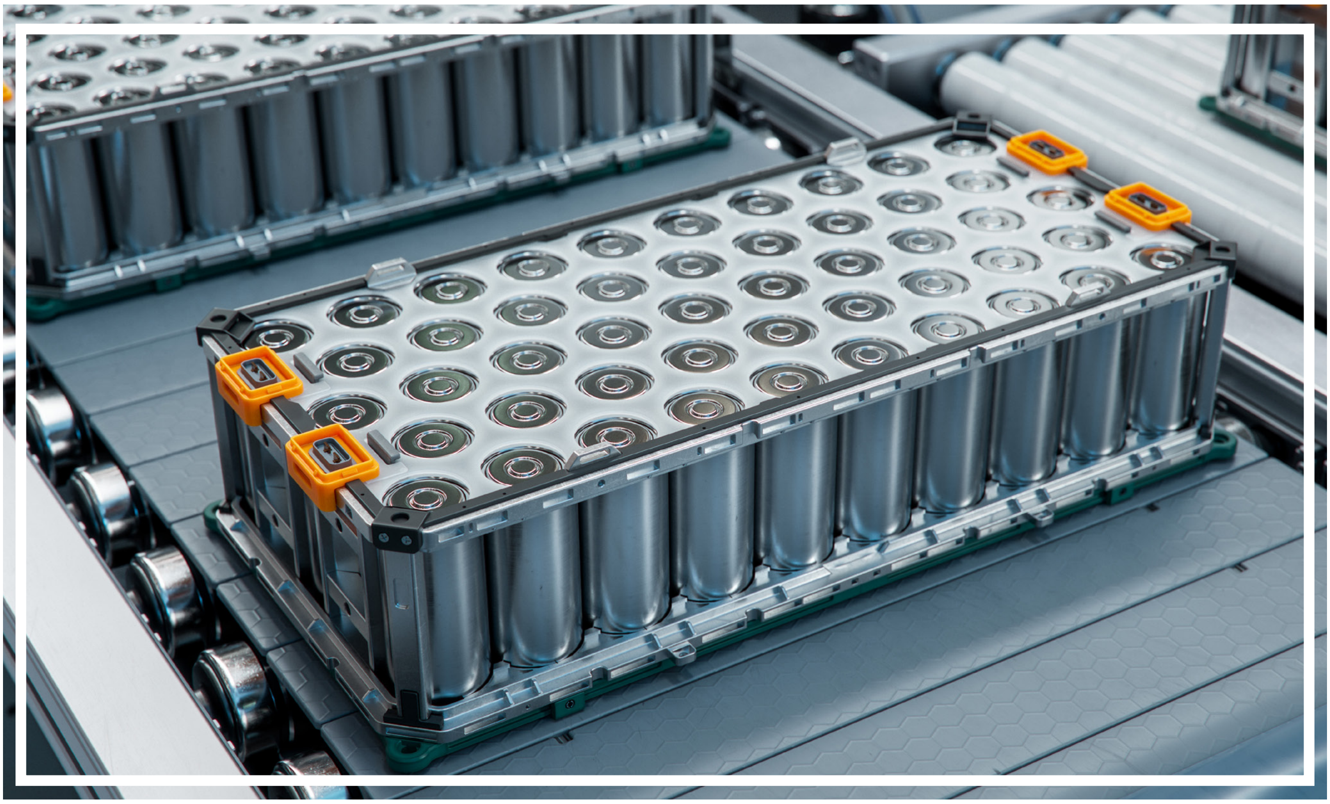
In the utility-scale energy storage segment, a mix of technologies, including lead-acid, redox flow, and high-temperature batteries, such as sodium sulphur have already been announced or deployed in large-scale projects. New alternative battery technologies in the utility-scale segment are expected to continue scaling up and gaining market share as they achieve longer lifetimes, lower costs, and economies of scale. The potential market here could reach gigawatt-scale in the short-to-medium term.

In the consumer electronics segment, fast charging and downsizing geometries and battery packs remain crucial trends.

While flexible cell design and increasing miniaturisation could gain importance in the long-term, lithium-ion batteries are expected to maintain their dominance for major consumer electronics applications.

Nonetheless, the market share of alternative battery technologies depends on factors such as battery performance, cost, production scalability, and sustainability, which vary by country, technology producers, solution providers, and specific applications.

CONCLUSION



Despite challenges related to electrode potentials, ionic radii, and other factors, alternative battery chemistries hold promise for various applications in the automobiles, residential, utility-scale energy storage, and consumer electronics sector.

On the supply-side, technological research and development continues to be focussed on developing solutions across all components of batteries and battery lifecycle, including active materials, electrolytes, manufacturing processes, and end-of-life strategies. By addressing these challenges, alternative battery chemistries could find their place alongside lithium-ion batteries in the evolving energy storage landscape in the long-term.

Across all alternative battery technologies, metal-ion chemistries share production steps that closely resemble lithium-ion batteries. Consequently, they are generally more appealing, with the advantage of leveraging existing production lines and under similar manufacturing environments.

Alternative battery chemistries potentially offer lower material costs compared to lithium-ion batteries. Whilst initial costs for alternative battery technologies may be higher due to low production scales, however, real benefits appear, when gigawatt-scale markets and applications emerge, which will be crucial in achieving economies of scale improvements and cost reductions.

Non-lithium batteries generally rely on less critical raw materials. However, without large-scale applications and offtake comparable to lithium-ion batteries, the production and supply of lithium, nickel, and cobalt will remain crucial, particularly over the next decade.

Additionally, most alternative battery chemistries have lower energy density than lithium-ion batteries, which necessitates a larger quantity of raw materials to achieve the same storage capacity.

An analysis of patents and publications reveals that alternative battery chemistries, such as redox flow batteries, lithium-air, and aluminium-ion batteries show promise. Japan and China continue to lead in terms of patent applications and peer-reviewed publication related to these technologies. Despite the technological progress on these chemistries, the absolute level of research activity for lithium-ion batteries will continue to remain significantly higher in the medium-term.

Given that alternative batteries will invariably compete with lithium-ion batteries as a benchmark in the long-term, prioritising standards and compatibility will be crucial to their technological development and deployment. This involves aligning production steps, from components to cells, cell formats, and battery systems, as closely as possible with lithium-ion batteries. Establishing entirely new supply chains would be only feasible for chemistries with dedicated use cases, those serving sufficiently large markets and applications, in the medium-to-long term.

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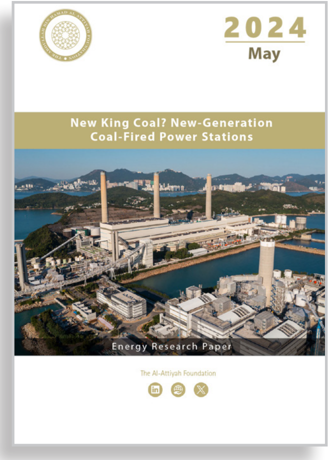

May – 2023

New King Coal? New-Generation Coal-Fired Power Stations

The prevailing belief is that the use of coal must cease to achieve net-zero emissions. However, new coal power plants, equipped with advanced ultra-supercritical, fuel cells, small supercritical, co-combustion, combined heat and power, and carbon capture, use and storage (CCUS) technologies offer enhanced thermal efficiency, reduced emissions, and increased flexibility in power generation.

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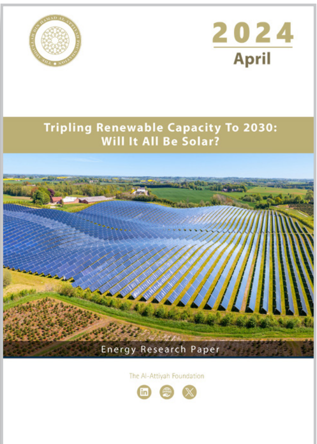

April – 2024

Tripling Renewable Capacity To 2030:Will It All Be Solar?

The 2023 United Nations Climate Change Conference (COP28) united parties around a pledge to triple current global renewable capacity from about 3.8 GW currently to reach 11 TW by 2030, placing renewables at the center of achieving global climate commitments.

March – 2024

Russia – China Energy Nexus

China has leveraged Russia's shift in energy trade focus from Europe to Asia, in the wake of Western sanctions imposed over the invasion of Ukraine. Chinese companies have seized the opportunity presented by discounted prices, increasing purchases of Russian energy.

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Our partners collaborate with The Al-Attiyah Foundation on various projects and research within the themes of energy and sustainable development.

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