Battery Materials - 2025 and beyond

The global energy demand has risen multi-fold over the decades. The pressing concern to supply energy all over the globe and to reduce the climate change impact caused by fossil fuels becomes the need of the hour to switch to reliable green energy with a suitable energy storage technology such as batteries.

As a state-of-the-art storage system, battery finds its major applications in sectors like consumer electronic goods, stationary and portable energy storage systems, grid energy, automotive sector, etc. Moreover, the global corporate and government mandates have been the proponents fostering the electrification of the mobility sector through their initiatives, regulatory policies, and regulations. As a result, these industries are now witnessing a prominent shift from energy rigorous to material-intensive systems.

Current battery technology and ongoing innovations

Apart from the well-established and quite aged lead-acid batteries, LIB (Lithium-ion battery) is currently widespread among all other battery types, with its application ranging from smartphones to electric vehicles. The current LIB technologies in use are NMC oxide batteries, lithium manganese oxide batteries, lithium NCA oxide batteries, lithium iron phosphate batteries, lithium cobalt oxide batteries, lithium titanate batteries. Among them, lithium nickel cobalt aluminum oxide is found to possess the highest specific energy density of 200 – 250 Wh/Kg and is relatively cheap at the same time, whereas lithium titanate exhibits a soaring life cycle of 3000 – 7000. This is a reason for the EV market leader Tesla to employ lithium NCA/NMC battery to get a better edge over its competitors, which intends to replace costly metals like cobalt with nickel-based chemistries. Exhibit 1 gives us an overview of the timeline of the development of various kinds of battery technologies over years and potential future battery materials.
Although each battery has its own advantage and disadvantages, high energy storing potential, shorter charging time, improved cycle life are the main advantages of LIB. The main challenge faced in using LIB is that their lifecycle and performance curves decline at elevated temperatures which raises substantial safety concerns over its usage in EV and electronic gadgets. Moreover, the abundance of lithium in the earth’s crust is only 0.002% – 0.006%, and also this battery technology makes use of Nickel and Cobalt which are other critical elements on earth. Therefore the world automotive production leaders are expected to face the crisis of cobalt and lithium shortage due to geopolitical reasons.

Owing to this scenario, various corporates and institutes have collaboratively engaged to innovate on battery materials as per battery technology to cater to future energy demand and certain critical material crises.

**Future battery concept: Technology and material innovations**

The prolonged stagnant periods of battery technology development have seen significant cutting edge breakthroughs in the recent past. The technology drift from heavy lead-acid batteries to more compact, sustainable, efficient battery technologies is imminent. The state-of-the-art LIB stands as one most significant groundbreaking technology in the energy sector. Also, we are in the imminent stage and about to witness disruptive technologies employing more sustainable materials for their operation in the post-lithium era.

**Innovation in battery technologies**
There have been immense battery-related technology innovations for over a decade. The top five most researched battery types based on the patents filed are flow batteries, solid-state batteries (Na, Li based), sodium ion, lithium sulphur, and zinc-air battery. Apart from these, there are various other innovative battery types such as solid-state batteries, flexible batteries, paper batteries, etc. Exhibit 2 shows us the comparison of various future battery technologies to be commercialized in the next few decades.

- **Sodium sulphur battery**: LIB’s may be employed widely, but the world’s largest battery in Dubai is sodium sulphur based. Unlike LIB which lasts for only 2 – 3 years, they last up to 15 years. However, the inexpensive sodium and sulphur has certain handling issues and the high operating temperature required to liquefy sodium is highly likely to exacerbate the ceramic separator
- **Sodium-ion batteries**: The dominance of sodium-ion batteries comes from their cheap cost and natural abundance over its LIB counterpart. The abundance of sodium to lithium in the earth’s crust is in a 23600 ppm to 20 ppm ratio. Also, the cathode and anode used in sodium-ion batteries are from abundantly available transition metals like iron, manganese, vanadium, titanium. Moreover, sodium-ion batteries can function without employing cobalt, thus making them a suitable sustainable candidate in future battery technology.

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<th>EXHIBIT 2: Future battery technologies and their comparison</th>
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<td>Parameters</td>
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- **Solid-state batteries**: The demand for solid-state batteries arose mainly because of the safety issues experienced by the aqueous electrolytes. Since the ionic conductivity of solid electrolytes is good, and they don’t require an embedded cooling system (owing to their
high melting point), they seem quite promising on replacing the liquid electrolyte batteries on commercial grounds.

- **Lithium sulphur battery:** The energy density of commercial LIB hardly goes par 300 Wh/kg, therefore it has become imperative to find an optimized solution to meet the future energy storage needs. Being one of the richest elements, sulphur also has a higher theoretical energy density of 1,625 mAh/kg, which makes it a prominent contender in the future battery technology race. However, researches are carried on to overcome its intermediate dissolution complication and volume change problems encountered during its operation.

- **Iron air battery:** The availability and abundance of iron in the earth’s crust make it very promising. Also, the iron air battery costs less than one-tenth of the LIB and it has a high probability of becoming the lowest cost energy storage system.

- **Zinc-air battery:** Zinc is one of the abundant materials in the earth’s crust and they are well suited for microgrid applications, where lithium stands no chance to compete on cost. NantEnergy, Arizona based company has overcome the limited reusability issues associated with Zn air batteries by their novel technique and has extended their cycle time. Moreover, they are free from any kind of toxic emissions.

- **Redox flow batteries:** Vanadium redox flow battery is the most popular RFB among all the others, but it is highly likely to face metal shortage issues in the near future. Although, the photovoltaic intermittency problems are overcome by the current rechargeable flow batteries (ZBFB, IRFB, HBFB, AORFB, VRFB); the hunt for new, abundant, inexpensive, recyclable, sustainable materials to attain industrial acceptance is still on. Air-breathing sulphur flow batteries, solar redox flow batteries, Metal CO$_2$ flow batteries are some of the niche emerging technologies.

- **Aluminum air battery:** Since cobalt, lithium, phosphorous are facing substantial chances of supply chain problems, a high valent aluminum-air battery seems promising as it has a higher theoretical energy density significantly greater than the current LIB technology.

- **Lithium-air battery:** Studies were carried out in the last 20 years on this state-of-the-art technology with three different electrolytes. The non-aqueous electrolyte lithium-air battery is more concentrated, because of its potential to achieve high energy density. Even though lithium anode possesses higher potential versus traditional hydrogen electrodes, the major challenge faced is the lithium dendrite formation during the charging operation, which renders it unsuitable for commercialization.
- **Paper batteries:** The paper batteries will provide a solution for the space constraints faced by most of the commercial batteries in use. The carbon nanotubes and cellulose-based sheets used in paper batteries will aid in shrinking the contemporary device size. Owing to its ultrathin size, durability, biodegradability nature, it is extensively used in electronic gadgets.

- **Hydrogen cell:** A nascent technology in the future battery race is the hydrogen fuel cell, which possesses nearly 10 times the energy to weight ratio compared to its counterpart LIB. Even though hydrogen can be harnessed everywhere without any supply chain issues, its flammability nature and the expenses involved in storing these gases are

Apart from the above mentioned technologies, there are various other novel battery technologies that are being conceptualized, such as cobalt-free LIB, gold nanowire batteries, graphene batteries, foam batteries, laser-powered super micro capacitors – based on the fast-charging principle are gaining more traction among the research community. However, they are still in the postulation stage and their commercialization is expected to be beyond 2040 or 2050.

**Future battery materials**

The demand for batteries with enhanced energy density and better safety has become a necessity to suffice the growing energy needs, and therein a strong pursuit for green chemistry and efficient battery materials has begun. The key existing battery materials used currently are mentioned in this article. Also, the emerging battery materials for next-generation battery technologies to achieve our sustainable development goals are discussed in this section.

- **Sodium:** Sodium, which is very cheap and abundant in nature is in the limelight among the research group, and is considered as a replacement material for lithium in future batteries. Studies are carried out to compensate for the relatively low energy density offered by sodium-ion batteries.

- **Aluminum:** Several tech sector communities have claimed aluminum to be the emerging material post-lithium era. Also, aluminum air battery has a higher operating range, is environmentally safe, and cost-effective when compared to LIB’s, when used as an anode material. They are extensively used as current collectors in current LIB technology.

- **Lithium:** Lithium metal has high potential to be used in various future
battery technologies such as lithium-air, lithium sulphur, advanced lithium-ion batteries such as LTO, and so on, as an anode material.

- **Magnesium:** One of the richest elements on the earth has also gained the spotlight in recent years. Nowadays, magnesium-based electrolytes along with sulfur-based cathodes are being researched extensively.

- **Nanomaterials:** Nanomaterials such as nanowires pose a huge possibility for future batteries. The breaking down of nanowires while recharging can be easily overcome by immersing it in a gel electrolyte, where it becomes wear-resistant, thus extending its cycle life.

Apart from the above-mentioned materials, the periodic chart gives us a clear depiction of the feasible future battery materials which are very likely to rule the energy storage market in the upcoming decades. Among these, silicon is the most researched anode material possessing ten times larger energy density than conventional graphite anode, has also gained an edge over its counterpart in the sustainability aspect since the former can be derived from plant-based sources like barley husk ash. An overview of various potential elements/materials to be used in future battery technologies is shown in *Exhibit 3.*

**Investment activities in the battery technology domain**

The global market investment for advanced battery materials is projected to reach US $110 billion by 2024. There have been wide commercial activities in battery technology, material innovation domains in the past decades. A few major activities in recent times are as mentioned below:

- South Korea has planned to invest the US $35.4 billion over the period of 10 years to be a global leader in battery tech.
- UK has invested the US $3.58 billion to set up a gigafactory with the
capacity to produce 300,000 LIB for automotive applications.

- Energy Renaissance has received a new investment of US $1.2 billion from the Australian government initiative to boost battery production.
- The lithium triangle - Argentina, Bolivia, and Chile (known as ABC’s of lithium in the world) has nearly 75% of the global lithium reserves. The Bolivian government has formed a joint venture with a German firm to invest over the US $1.3 billion to promote industrial use of lithium.
- EU invests €665 million in the fuel cells and hydrogen technologies both for energy and mobility applications
- North American VCs and equity firms invest more than US $500 million in 25 battery startups.
- Sumitomo Metal Mining, a Japanese company has announced to invest the US $424 million to boost cathode material production to meet the EV demand.
- Chinese tech group Qingdao (Kunshan) Energy Development has planned to invest US $153 million in solid-state batteries starting from 2021.
- India’s largest oil refiner, Indian Oil Corporation has teamed up with Israel’s aluminium air battery start-up, Phinergy Inc. India having approximately 600 million tons of bauxite reserves, has invested heavily to become the world’s second-largest aluminium smelter.

**Conclusion**

The energy technology companies are constantly striving to enhance the sustainability feature of batteries through various avenues. The critical properties which will play a major role in deciding the promising battery candidates are raw material abundancy, cost competency, energy density, emission toxicity, durability, operational efficiency.

The state-of-the-art LIB batteries face certain toxicity and supply chain issues, and so, finding suitable replacement technology is of primary concern among the sustainable battery community. Although lithium-sulfur and lithium-air batteries have shown satisfactory results on a research scale, the time period for their commercialization and the energy-intensive mining step involved along with the possible depletion of lithium resources on the earth’s crust are some of its inherent setbacks.

The need to search for sustainable battery materials is of primary concern and this necessity made the industry explore different bio-based materials, for e.g.: cellulose-based materials as potential electrode binders. These continuum novel researches will help us attain our sustainable goal, at the same time not compromising on the battery performance.
On a concluding note, until various potential battery technologies and battery materials are in the nascent conceptual stage, it is important that existing materials and battery designs are engineered to provide high battery capacity and energy, longevity and also see that the used materials are cost-effective, abundant and recyclable in nature, so as to achieve circular economy and lead a sustainable route in the future.