**Secondary Batteries, Accelerating Advancement of Sodium Batteries**

**https://www.sigmaaldrich.com/US/en/technical-documents/technical-article/materials-science-and-engineering/batteries-supercapacitors-and-fuel-cells/electrode-materials-for-lithium-ion-batteries?srsltid=AfmBOopZnRymdAlmz6jmgKt3KoPI-yya5aokNpDVCXYQ-eUWRJ565IJt**

In October 2023, ARPA-E awarded $3,198,085 to the Massachusetts firm 24M Technologies to develop a new sodium-ion battery specifically for EVs. “24M’s cell design will incorporate (1) its ultra-thick SemiSolid cathode made up of advanced cobalt-free, nickel-free sodium cathode active material, (2) an advanced wide-temperature, fast-charging electrolyte developed using machine learning and automated high-throughput screening technology, and (3) a sodium super ionic conductor,” ARPA-E explained (Casey, 2024).

Argonne has been replicating the nickel-manganese-cobalt (NMC) cathode strategy for sodium battery research. The result is a layered sodium nickel-manganese-iron oxide formula that allows for the efficient insertion and extraction of sodium. “The absence of cobalt in the cathode formula mitigates cost, scarcity and toxicity concerns associated with that element,” the lab notes. A research team at Argonne developed the lithium nickel-manganese-cobalt (NMC) cathode material for EV batteries, which General Motors deployed in its Chevy Volt and Bolt cars. The key to the NMC architecture was to arrange the atoms in layers, enabling the lithium to flow more efficiently (Casey, 2024).

Casey, Tina (2024) Clean Technica. Buh-Bye, Conflict Minerals: US Gets First Sodium-Ion Battery Factory. <https://cleantechnica.com/2024/04/30/buh-bye-conflict-minerals-us-gets-first-sodium-ion-battery-factory/>

Secondary batteries are also known as rechargeable batteries, and can be recharged by passing electricity through the cells. During recharging, the electrodes are restored to their original states by a reverse current. Even though we are discovering new domestic sources of lithium in the U.S., including mines, battery recycling, and next-generation brine recovery, cobalt, nickel, and manganese are also involved. Sodium-ion batteries contain no cobalt or nickel. The goal is to formulate sodium-ion batteries with a higher energy density than phosphate-based lithium-ion batteries (Casey, 2024B).

Paleja, Ameya (2025) Interesting Engineering, World’s largest EV battery maker unveils 373-mile-range swappable batteries,

<https://interestingengineering.com/innovation/battery-swapping-stations-catl-china>

Founded in 2011, CATL is the battery provider for the likes of Tesla, BMW and Volkswagen to name a few of the leading electric vehicle makers. CATL has developed the Choco-swap ecosystem, where batteries can be swapped on electric vehicles in about 100 seconds. Much like #92 and #95 versions of gasoline available at gas stations, CATL unveiled two versions of its swappable batteries, dubbed #20 and #25, with both available in lithium-iron-phosphate (LFP) and ternary versions with capacities ranging from 42 kWh to 70 kWh. They have a range between 248 – 372 miles (400 – 600 km) and will be available for vehicles of class A0 and A/B (Paleja, 2025).

Kutz, Ben (2024) World Crunch, The EV Battery Race Is Over — China Won, <https://worldcrunch.com/business-finance/china-electric-vehicles>

China’s dominance in the battery market is staggering. According to SNE Research, more than half of all electric car batteries built in the world come from Chinese companies, with CATL alone accounting for over one-third of global production. And it’s not just about factories in China anymore; Chinese firms have set up shop in Europe too. Last year, CATL inaugurated its first non-Chinese plant in Arnstadt, Germany. The facility churns out enough batteries annually to power 200,000 to 350,000 electric cars, depending on battery size — a total capacity of 14 gigawatt-hours. Initially, CATL had bigger plans, eyeing 100 gigawatt-hours of production in Germany. Those ambitions were later scaled back, with the company opting to build a plant in Hungary instead. Meanwhile, Germany’s local efforts look meager in comparison. UniverCell produces just 1.5 gigawatt-hours annually in Flintbek, near Kiel, and Swiss company Leclanché has a facility in Willstätt, near Offenburg, with a capacity of one gigawatt-hour.

In a secondary battery, lithium ions or sodium ions store energy by creating an electrical potential difference, or voltage, between the negative and positive poles (electrodes) of the battery. There is a separator, an insulating layer, which divides the two sides of the battery and blocks the electrons while still allowing the lithium ions or sodium ions to pass through. To charge the battery, lithium ions (sodium ions) move from the positive side of the battery to the negative side through the separator, and when discharging, the ions move in the reverse direction. The movement of ions, lithium or sodium, causes the electrical potential difference, or voltage. When electronics are connected to a secondary battery, the electrons which are blocked by the separator are forced to pass through your device and power it.

There are five integral parts of a secondary battery cell–the separator, electrolyte, current collectors, negative electrode, and positive electrode. The separator is a membrane located between the electrodes to prevent physical contact without compromising the flow of lithium ions. Aluminum and copper are the most commonly used current collectors for the positive electrode and negative electrode. Acting as a barrier, the passivation layer reduces further decomposition of the electrolyte during the cycle life of the cell. Secondary batteries can use either liquid electrolytes or solid electrolytes. The electrolyte acts as a conductive medium that allows ions to move between the anode and cathode, essentially facilitating the flow of current during charging and discharging by transporting the positive ions between the electrodes. A current collector facilitates electron flow from large area electrodes to the cell terminals. The positive electrode uses aluminum foil as a current collector while the negative electrode uses copper foil. Graphite is the preferred material for the negative electrode due to its stability over many cycles of expansion during charge, contraction during discharge, abundance, and low cost. It also has a reasonably low potential.

Jules Verne used a sodium battery to power Captain Nemo’s submarine in his 1870 novel 20,000 Leagues Under the Sea. Rechargeable liquid-metal batteries such as lithium-ion are used for industrial power backup, [electric vehicles](https://en.wikipedia.org/wiki/Electric_vehicle) and for [grid energy storage](https://en.wikipedia.org/wiki/Grid_energy_storage). Sodium batteries have garnered more research in recent years as the mining and environmental impacts of lithium batteries have become more consequential. Lithium, which can be costly to mine, is currently the main component in most electric batteries. Lithium extraction can result in water shortages, biodiversity loss, damage to ecosystem functions and soil degradation. When lithium is produced using evaporation ponds, for example, it takes approximately 2.2 million liters to produce one metric tonne (Elton, 2022). Lithium has uneven geographic distribution, high environmental impact, and high cost. Future batteries could run on sulfur or sodium, which are more abundant than lithium on the planet. However, because sulfur reacts to oxygen, sulfur-based batteries would need to be manufactured in oxygen-free environments. Solid-state batteries are another option, which use solid instead of liquid electrodes and electrolytes. The more power you can pack into smaller cells, the farther electric vehicles can travel between charging points, and thus have a lower cost.

One benefit of batteries is to store summer heat to use during winter, and there are many different types of salts to choose from for sodium-ion batteries. Sodium or lithium is the cathode, or charge carrier, and both of these elements are in the same group in the periodic table, and thus have similar characteristics. However, aqueous sodium batteries are different from lithium batteries. Solar panels convert light from the sun into energy, but the solar panels also are heated by the sun, and this heat can be stored with salt batteries. Lian Blijlevens of Radboud University said, “The heat can be extracted by a solar boiler and used to heat your house or shower. However, in summer you always generate more solar heat than you use, and in winter you have less. So what we need is a way to preserve that heat (Radboud University, 2023).” Batteries are increasingly needed to store energy from intermittent renewables like wind and solar. Many batteries are presently built with rare earth metals like lithium, graphite, and cobalt. To achieve climate neutrality, the EU will require 18 times more lithium than it currently uses by 2030 and almost 60 times more by 2050. European Commission President Ursula von der Leyen said in September 2023 that "lithium and rare earths will soon be more important than oil and gas (Elton, 2022)."

The current goal in secondary battery research is making a cost-effective and sustainable future alternative to lithium-ion batteries for electric vehicles and grid. Originally developed for electric vehicles in the 1980s and 1990s, mass commercialization, including cost reductions and scale, of sodium metal chloride batteries has been stalled by its cost structure. The chemical symbol for sodium, the sixth most abundant element in the Earth’s crust, is Na, for the Latin natrium. One of the roadblocks to commercializing sodium-ion (NA+) battery technology has been their low energy density, and while sodium-ion batteries do not yet have sufficient energy density to power vehicles over long distances, they are ideal for urban driving.

In the race to develop electric vehicle batteries which can outlast the lifetime of the car, the US has currently mandated that batteries retain 80 percent capacity even after eight years of operation. Lithium batteries are more expensive to produce than sodium batteries, especially the ones containing pricey metals like cobalt and nickel. The lithium battery supply chain depends on Chinese suppliers, which boasts battery makers and raw material producers. In order to bring lithium battery and sodium battery charging times closer to the duration of a refueling process for vehicles with combustion engines, weight must be reduced, and efficiency and range should be increased. In order to commercialize electric vehicles over gas combustion vehicles, charging should be faster, safety needs to be guaranteed at all times, and maintenance costs should be reduced. Around 800 cycles is significant because that’s beyond most consumer electronics and starts to get into EV and grid storage applications, and even space-based applications that require a high cycle life.

Lithium-ion and sodium-ion batteries have similar electrochemical mechanisms, with both realizing energy storage and release through the reversible disengagement and embedding of cations between the positive and negative electrodes. The anode of both types of batteries is carbon, with the difference that the cathode material of lithium-ion batteries contains lithium ions, while the cathode material of sodium-ion batteries contains sodium ions. The lithium salts in the electrolyte (the liquid that helps ferry charge between the battery electrodes) are traded out for sodium salts.

In standard laboratory tests for batteries, which do not replicate real world conditions, new battery designs are evaluated by discharging and charging over multiple cycles to determine if the battery design is reliable and has an acceptable life expectancy. In the real world, an EV battery pack powers the car in the high traffic of the cities, on the highways, at frequent traffic lights, or staying parked for long hours at home or office parking. In reality, batteries last longer with frequent acceleration, braking that charges the batteries, stopping to run an errand, and letting the batteries rest for hours at a time (Geslin et al., 2024; Paleja, 2024). Geslin et al. (2024) designed four types of EV discharge profiles, including a consistent and dynamic discharge setup using real-world driving data. Testing 92 commercially available lithium-ion batteries over two years, the team found that the battery life climbed as the profiles reflected more real-world driving behavior. This study showed that short and sharp EV acceleration slowed the degradation of batteries, and pressing the pedal hard slows down the battery’s aging instead of hastening it. The sweet spot for aging was between continuous charge-discharge cycles, like delivery vehicles, and sitting idle for longer durations.

***U.S. Domestic Lithium Deposits***

The domestic lithium pipeline supply chain is still problematic to the extent that it involves digging new surface mines, but an alternative solution has been emerging in the form of geothermal brine. By the mid-20th century lithium was a common input for the metallurgy, pharmaceutical and ceramics industries among others. Most famously, lithium was also among the original ingredients in 7-Up. Lithium mining activity in the U.S. has dwindled down to just one operation by the time the EV market took off, that being the 1960s-era Silver Peak mine in Nevada. Like the rest of the world, the US has been depending on lithium from just a few countries for its EV batteries. Australia and Chile dominate the market, with China and Argentina also in the running. As for lithium deposits in the United States, In 2020 the US Geological Survey identified five states with major deposits: Arkansas, California, Nevada, North Carolina, and Utah. A massive discovery in Maine also occurred in 2021, after the report was published. USGS also noted that smaller deposits occur in Arizona, Colorado, New England, New Mexico, South Dakota, and Wyoming. The problem is convincing local residents and environmental organizations that large swaths of the countryside should be torn up for the sake of EV batteries (Casey, 2023C).

The Department of Energy has been supporting the development of a geothermal brine supply chain for lithium-ion EV batteries, deploying a technology called Direct Lithium Extraction. The basic idea behind DLE is to pump geothermal brine to the surface, extract the lithium with particles of adsorbent material, and then send the spent brine back underground. The operation involves far less surface disruption than conventional mining. It also eliminates the use of vast open-air lagoons used in conventional lithium brine extraction. The Lawrence Berkeley National Laboratory found that new DLE technology in the Salton Sea could lead to the production of more than 3,400 kilotons of lithium, or enough to manufacture more than 375 million EV batteries. The Salton Sea also happens to be the location of 11 geothermal power plants, and the Department of Energy is among those spotting an opportunity to piggyback DLE operations onto geothermal facilities. The figure of 3,400 kilotons is based on the potential for expanding geothermal resources in the Salton Sea region (Casey, 2023C).

**LDES Batteries, Long Duration Energy Storage**

Battery storage options provide flexibility and reliability for the electric grid, and enable the use of more renewable energy and reduce the need for costly grid upgrades, as storing energy is an important part of a low-carbon grid. Batteries are useful for renewable electricity sources such as wind and solar, where energy demand does not align with peak power production, due to increased use of intermittent renewable energy sources which cannot be turned on to meet peak demand the same way fossil-fuel sources can. To smooth demand for electricity, utilities charge more for power at peak times and less when there is excess supply. Batteries can store this excess energy supplied during the daytime when the sun is shining, and supply it overnight. Utilities and homeowners can use long duration energy storage (LDES) batteries to store energy days, or even years, as these batteries allow buildings and manufacturers to buy power when it's cheapest.

The Biden Administration set a goal of achieving private sector lift-off of the energy storage sector in the U.S. by 2030, along with net zero emissions by 2050 and 100% carbon-pollution free electricity by 2035. According to estimates by the U.S. Energy Department, the U.S. grid will need 225-460 GW of LDES capacity for a net-zero economy by 2050, representing $330B in cumulative capital requirements. Furthermore, net-zero pathways that deploy LDES by 2050 will result in $10-20B in annualized savings in operating costs and avoided capital expenditures compared to pathways that do not.[[1]](#footnote-0) According to the U.S. DOE, there are three market-related benefits of batteries for energy storage. One, they support and complement the expansion of variable renewables, as LDES can provide stability and flexibility to the grid as variable renewables expand, and LDES can also reduce the cost of grid expansions by providing optionality and planning flexibility. Two, they enhance grid resilience from extreme weather events, and reduce the need for new natural gas or coal capacity. Three, they diversify the domestic energy storage supply chain, reducing the need for lithium-ion manufacturing buildout, in addition to increasing the potential availability of lithium-ion for EVs. However, improvements are necessary in technological performance and costs curves to bring costs down, market and regulatory mechanisms to encourage investment and development of LDES, and there needs to be supply chain development and planning, so we can diversify away from reliance on China.

**Lithium Mining and Extraction**

Some of the concerns with lithium mining include environmental impacts, including water shortages and the use of toxic chemicals, and geopolitical risks and supply chain vulnerabilities, as China currently dominates the lithium market. It has been estimated that extracting a single ton of lithium, according to a 2018 WIRED magazine report, requires approximately 500,000 liters of water, with this wanted demand posing a direct threat to other water users. Using brine ponds to extract lithium poses a threat of contaminating existing, precious freshwater reserves. The chemicals involved in lithium extraction pose another environmental issue, as they are extremely toxic. "The release of such chemicals through leeching [sic], spills or air emissions can harm communities, ecosystems and food production," a report from international environment activism group Friends of the Earth reports. "Moreover, lithium extraction inevitably harms the soil and also causes air contamination" (Zaremba, 2024).

Vera et al. (2023) argues that because of mining constraints, opposition to lithium projects ensures that the lithium mining industry is slow to react to demand fluctuation. In South America’s lithium triangle, the salt flats of Argentina, Bolivia, and Chile, which overlaps with the Atacama, the world’s driest desert, lithium is produced via open-air brine evaporation pits. When lithium is extracted using brine concentration and processed via evaporation, there are lower CO2 emissions, though it is water-intensive in arid regions, prompting concerns about the overuse of aquifers. Lithium is also produced from hard rock mining, mostly in Australia, whereby China processes that Australian material, as China has the only domestic hard rock and brine-based processing capacity. According to BMI, Benchmark Mineral Intelligence, 34% of lithium is mined in Australia, 28% in South America, and 20% in China. When lithium is mined from hard rock using energy intensive processes, it uses diesel-powered mining equipment and high-temperature processing (Vera et al., 2023; Hutchins, 2024).

An alternative process to extract lithium is known as direct lithium extraction (DLE), in which lithium is extracted from brine using thermal or chemical processes. According to BMI, DLE operations, which take a fraction of the land required by evaporation ponds, account for 4% of today’s lithium and will reach 12% by 2030. DLE approaches can mean that there is minimal water depletion from the subsurface aquifer and, if used with renewable power, there are minimal emissions in the process. In fact, oftentimes with DLE brines can be reinjected so in theory the balance of the aquifer is not changed. However, DLE production costs can vary greatly depending on brine composition, temperature, and depth, as well as other conditions at a project site and the specific technology used. DLE approaches such as ion pumping or Li+ [lithium]-selective membranes, are new and will require more engineering efforts to commercialize their use, though older methods such as ion exchange, solvent extraction, or electromembrane processes, simply need to be adapted to the complexity of lithium-rich brines.” (Vera et al., 2023; Hutchins, 2024).

Natural brines are saltwater sources found in geothermal environments. The U.S. researchers have developed a three-chamber electrochemical reactor that tackles lithium extraction in a novel way. Unlike older methods, this reactor uses a middle chamber containing a porous solid electrolyte, which precisely controls ion flow. This setup not only enhances the efficiency of lithium extraction but also minimizes unwanted chemical reactions. A standout feature is the reactor’s cation-exchange membrane, which keeps harmful chloride ions away from the electrodes. This innovation prevents the production of toxic chlorine gas and reduces hazardous byproducts, offering a cleaner solution to lithium extraction. Central to this cutting-edge system is the lithium-ion conducting glass-ceramic (LICGC) membrane. This advanced material selectively allows lithium ions to pass through while blocking others, ensuring high purity and efficiency. The result? Lithium extracted at an impressive 97.5% purity, ideal for producing high-grade lithium hydroxide—a critical component for EV and renewable energy batteries. One of the main challenges is the buildup of sodium ions, which can hinder lithium transport and increase energy consumption. To address this, researchers are exploring strategies like adjusting current levels, using surface coatings, and employing pulsed currents to optimize the system (Smith, 2025).

Smith, Noah (2025) Jason Deegan, The U.S. Puts China on the Back Foot With a Breakthrough That Advances the Lithium Race, <https://search.app/zePYyHLQrK7UCqvG9>

**Battery Components**

The specific components and their configurations may vary depending on the type of battery chemistry. For example, wet-cell batteries are often used in cars, cell phone towers, and planes, while dry-cell batteries are usually found in hand-held electronics. In general, an electrode is an electrical conductor which makes contact with a non-metallic part of a circuit. In a battery, the electrodes connect the battery terminals to the electrolyte. When discharging, the electrode at the positive terminal is known as the cathode and the electrode at the negative terminal is known as the anode. When charging, the negative electrode becomes the cathode, and the positive electrode the anode. At the anode a battery oxidizes (discharge) and reduces (charge), while at the cathode the battery relies on the reversible reduction (discharge) and oxidation (charge).

1. Anode: The negative side of the battery, usually made of graphite
2. Cathode: The positive side of the battery, typically made of nickel, manganese, and cobalt oxides
3. Electrolyte: A chemical solution that moves lithium or sodium ions between the anode and cathode
4. Separator: A porous material that prevents the anode and cathode from touching
5. Current collectors: Positive and negative current collectors that allow the electrical current to flow through a device
6. Housing: Provides physical protection and prevents external contamination

**Electrolyte**

We need to develop innovative electrolyte materials for sodium-ion batteries that can be integrated into prototype cells and sodium-ion packs that produce a long life cycle and high energy density.

Secondary batteries, such as those used in electric vehicles and energy storage systems, generally rely on flammable liquid electrolytes, which necessitates research to explore the use of solid electrolytes and the metal lithium (Li) in all-solid-state batteries. In the operation of all-solid-state batteries, lithium is plated onto an anode, and the movement of electrons is harnessed to generate electricity. During the charging and discharging process, lithium metal undergoes a cycle of losing electrons, transforming into an ion, regaining electrons, and being electrodeposited back into its metallic form. However, indiscriminate electrodeposition of lithium can quickly deplete the available lithium, leading to a significant reduction in the battery’s performance and durability (Lee et al., 2024).

According to McKinsey and Co., by 2030, solid-state batteries, which use a solid electrolyte instead of a liquid or gel, will begin to become available, which would allow for higher energy densities and longer driving ranges. The electrolyte is the substance through which ions move as they go from side to side during charging and discharging. Solid-state batteries might be more common in high-end models and popular with people who want the longest possible ranges, with sodium-ion batteries more common in low-cost EVs for people who live in cities or suburbs and don’t place a high premium on driving range.

**Anode**

The battery anode is the negative electrode, negative terminal, where electrons are lost, or oxidized, or released into the external circuit. At the anode, anions (negative ions) are attracted to and react, releasing electrons. The anode is usually made of a metal that oxidizes and sends electrons to the cathode, the positive electrode. This electrochemical reaction produces electrons, or generates electricity. The anode stores power during charging and then releases it when the battery is in use.

Graphite is currently the most commonly used material for anodes in lithium batteries, however, materials like silicon offer much greater energy capacity than graphite. Silicon tends to expand during internal reactions within the battery, however, which can compromise its stability and safety. Korean researchers have engineered a special binding material that prevents a high-capacity silicon anode from expanding, with the result being a lithium battery with ten times the capacity of those with graphite anodes (Lee et al., 2024; Shavit, 2024). Lee and his research team developed an anode protection layer composed of a functional binder (PVA-g-PAA) for all-solid-state batteries, which exhibits exceptional lithium transfer properties, preventing random electrodeposition and promoting a process of ‘bottom electrodeposition,’ which ensures that lithium is uniformly deposited from the bottom of the anode surface.

German and Taiwanese researchers have developed a Large-Footprint Lithium Ceramic Battery (LLCB) for electric vehicles, which uses a silicon composite material for the battery anode, which offers 10-times higher capacity density compared to the graphite anodes. The battery uses a solid-state electrolyte as opposed to a liquid electrolyte, which means the battery is non-flammable and increases safety against thermal runaway. It also prevents potential short circuits caused by leaking electrolyte fluid in the event of a spill. The silicon anode enables faster charging times as compared to current fast charging intervals of around 30 minutes by reducing the charging time by more than 80 per cent. The battery can be charged from five to 60 per cent within five minutes, to cover an average distance of 300 km. After eight minutes, the battery is charged to 80 per cent and can cover a further 100 km (Mishra, 2024).

U.S. researchers discovered that properly processed rice hull ash can yield a carbon form, which could outperform graphite as the anode in battery applications. This "hard carbon" has a unique nanostructure that allows it to store more energy than graphite in lithium-ion batteries. Producing hard carbon through the combustion of rice hull ash is more sustainable and efficient than traditional methods that require high temperatures and oxygen-free environments. This could serve as a domestic alternative to imported graphite, reducing reliance on foreign sources for making battery electrodes. Rice hull ash is primarily composed of silica (about 90%) and carbon (about 10%), and the research team has developed a method to extract high-purity silica from rice hull ash. In their press release the researchers noted that “Once the silica is partially removed from the rice hull ash through a process called depolymerization, the remaining ash is about 60%-70% carbon”. Initially, the carbon residue from rice hull ash was believed to be amorphous, lacking a defined structure. However, advanced spectroscopic analysis revealed the presence of tiny graphite structures embedded within the amorphous carbon matrix. This unique combination, known as hard carbon, exhibits enhanced properties compared to pure amorphous carbon. This unique combination of amorphous carbon interspersed with tiny graphite structures is known as hard carbon (Yu et al., 2024).

**Cathode**

A battery's cathode is the positive electrode, positive terminal, where electrons are gained, or reduced, or absorbed from the external circuit. At the cathode, cations (positive ions) are attracted to and react, gaining electrons. During charging, electrons flow from the cathode to the anode, storing energy for powering devices. In a rechargeable battery, the cathode becomes an anode during charging. Performance of the cathode declines with repeated discharge and charge.

Zuo et al. (2024) researched ways to prevent cracks in the sodium-oxide cathode, by using microscopic particles of nickel in the core, which provides high capacity for energy storage, and cobalt and manganese in the shell, which gives the surface structural stability during the charge-discharge cycling. To prevent the cathode’s energy storage capacity from declining during cycling, due to the formation of cracks in the particles during cycling, formed due to strain arising between the shell and core in the particles, the team simulated heat treatment conditions that would eliminate the cracks in the gradient particles. The heat treatment consisted of two versions of hydroxide, a precursor material used to start the synthesis process, one with the metals distributed in a gradient from core to shell and another with the three metals evenly distributed throughout each particle.

**Electrode Binders**

Electrode binders are an essential component of batteries, especially lithium-ion batteries, that help maintain the battery's performance and longevity. They provide structural integrity, by holding together the active material particles and conductive additives in the electrode.

They provide electrical contact between the active material particles and the current collector.

They provide ionic conductivity, as binders must allow lithium ions to move so the battery can charge and operate efficiently. And they respond to volume changes, as binders must be flexible enough to absorb the volume changes that occur in the electrode materials during charging and discharging. EV battery binders influence battery cost and performance.[[2]](#footnote-1)

One of the most common electrode binders, PVDF (poly-vinyli-dene fluoride), is a toxic PFAS chemical. Further, another toxic solvent, NMP (n-methylpyrrolidone) is also used in the lithium-ion battery manufacturing process to dissolve the temporary PVDF binder. In conventional EV battery manufacturing, the PVDF binder is a temporary fix needed to keep the material together until it is ready to be dissolved out, with the dissolving done by an NMP solvent. A U.S. research team at Nanoramic has replaced the PVDF binder with a carbon binding structure, which improves both the electric conductivity and mechanical properties of the battery, and eliminates the need for NMP solvent, which was replaced with water and alcohol. This new binder can be used in EV battery electrodes as well as other lithium-ion battery applications, in an effort to create a sustainable supply chain for electric vehicle stakeholders (Casey, 2024A).

**Electrostatic Capacitors**

Electrostatic capacitors are electronic components that store electrical energy in an electric field and enable ultrafast charging and discharging. They provide energy storage and power for devices ranging from smartphones, laptops, and routers to medical devices, automotive electronics and industrial equipment, as well as high-performance electronic devices, encompassing high-power electronics, high-frequency wireless communication systems, and integrated circuit chips. We need to improve the operating efficiency of electrostatic capacitors, so they can better contribute to power needs in sectors requiring robust power management solutions, such as electric vehicles and infrastructure development (Westenhaus, 2024B).

Electrostatic capacitors are typically made of two parallel metal plates separated by a dielectric,, which determines the capacitor's size, package, and frequency range. For a thin-film capacitor, the ideal dielectric material has a high dielectric constant, low dielectric loss, and high dielectric strength. Ceramic capacitors have a ceramic dielectric, and film and paper capacitors are also named for their dielectrics. Aluminum, tantalum, and niobium electrolytic capacitors are named after the material used as the anode and the cathode construction. The aluminum capacitors are A polarized capacitor with an aluminum can and an electrolyte solution of boric acid, and are commonly used in audio equipment and switched-mode power supplies. Tantalum capacitors are used in electronic devices that require stable capacitance, low leakage current, and reliability, such as medical equipment, aerospace, and military applications, however, they are susceptible to thermal runaway and explosion and fire risk.

A challenge with current electrostatic capacitors is that the ferroelectric materials used in capacitors have significant energy loss due to their material properties, making it difficult to provide high energy storage capability. To address this energy loss in ferroelectric capacitors, U.S. scientists created artificial heterostructures made of freestanding 2D and 3D membranes, with an energy density up to 19 times higher than commercially available capacitors while achieving an efficiency of over 90%. In capacitors, relaxation time is an internal material property that describes how long it takes for charge to dissipate or decay, as dielectric relaxation time can be modulated or induced by a very small gap in the material structure, which enables the manipulation of dielectric material in such a way that it doesn’t polarize and lose charge capability. Han et al. (2024) controlled the relaxation time of ferroelectric capacitors using 2D materials, and created a 2D/3D/2D heterostructure that can minimize energy loss while preserving the advantageous material properties of ferroelectric 3D materials (Han et al., 2024; Westenhaus, 2024B).

**Battery Recycling and Waste Disposal**

Direct recycling is a method that enables residual materials from battery cell production, as well as whole battery cells, to be mechanically dismantled into their valuable components. Unlike conventional methods, the main characteristic of direct recycling is that raw materials from battery cells are not reverted to their original state but are instead fed back “directly” into the cell production cycle. The method dispenses with the previously common energy-intensive chemical or thermal processing (O’Dea, 2024).

The current recycling rate for Li-ion batteries in the US and EU is around 5%, whereas 95% of lead acid batteries are recycled.[[3]](#footnote-2) A combination of technical constraints, economic barriers, logistic issues, and regulatory gaps has led to the low recycling rate for lithium-ion batteries. Two pathways exist to recycle lithium-ion batteries: 1) extraction of individual metals via smelting and/or acid leaching, and 2) extraction of intact alloy positive electrodes. Even though positive electrode components and the copper foil from the negative electrode are considered first for recycling, lithium recycling has increased in number too.[[4]](#footnote-3)

In terms of recycling and the circular economy, PVDF is one of the factors that make EV battery recycling difficult and expensive, as re-using the active material in electrodes typically requires an energy-intensive process of atomic breakdown and buildup. In the Nanoramic model the active material in NMC cathodes made with Neocarbonix can be reused directly (Casey, 2024A).

Lithium-ion batteries run everything from smartphones and laptops, to electric toothbrushes, and electric cars, and also are used to store wind and solar energy. In the future, as mineral deposits dry up, lithium-ion batteries will have to be recycled to recover the precious minerals used in their production, as the Earth does not contain enough accessible metal for us to mine forever. The batteries that we produce need to be safe, last a long time, and we need to recover the minerals when they reach their end of life. In order to meet our energy storage needs safely, we need to procure cheaper, more powerful batteries with fewer environmental costs. Large amounts of energy are created by mining metals to manufacture batteries, and this mining emits greenhouse gasses. A phone needs a different battery than an electric car, so not all lithium-ion batteries are the same, and thus we need recycling methods for each type of battery. Each cell in a lithium-ion battery contains numerous layers of metals, including lithium, nickel, cobalt, and manganese, and these metals layers do not always degrade in the same way. For example, some batteries can be crushed safely, but others cannot (Clean Technica, 2023).

***Methods of Recycling Batteries***

The first option wastes a lot of energy, and neither option recovers all the precious materials.

1. Melted down in a furnace
2. Dissolved in acid
3. Direct recycling- In this method, the battery is deconstructed without breaking any of the metals’ chemical structures. This is a gentler process that could help recover more materials compared to the previous, more destructive recycling methods.

**Recycling EV Batteries to Solar Farms**

Repurposing EV batteries for stationary storage can extend their usefulness for several years. These facilities are meant to prove the feasibility of giving EV batteries a second life as stationary storage before they are recycled. Doing so could increase the sustainability of the technology’s supply chain and reduce the need to mine critical minerals, while providing a cheaper way of building out grid-scale storage. 70% of decommissioned EV battery packs are suitable for a second life as stationary storage, with some packs not having enough life left in them, being too damaged from a collision, or otherwise faulty. By extending the life of a battery, we reduce the need for further exploitation of our natural resources, we reduce the demand for raw materials, and we generally encourage a more sustainable process (Aoun Angueira, 2023).

B2U says its technology allows batteries to be repurposed in a nearly “plug and play fashion.” They do not need to be disassembled, and units from multiple manufacturers — B2U has tested batteries from Honda, Nissan, Tesla, GM, and Ford — can be used in one system. The packs are stored in large cabinets and managed with proprietary software, which monitors their safety and discharges and charges each battery based on its capacity. The batteries charge during the day from both the solar panels and the grid. Then B2U sells that power to utilities at night, when demand and prices are much higher. B2U expects to add storage to a third solar facility near Palmdale next year. The facilities are meant to prove the idea works, after which B2U plans to sell its hardware and software to other storage-project developers. The SEPV Cuyama facility, located about two hours northeast of Santa Barbara, is the second hybrid storage facility opened by B2U Storage Solutions. It is a 20-acre parcel outside the tiny Southern California town of New Cuyama, a 1.5-megawatt solar farm that uses the sun’s rays to slowly charge nearly 600 batteries in nearby cabinets. Its first facility, just outside Los Angeles, uses 1,300 retired batteries from Honda Clarity and Nissan Leaf EVs to store 28 megawatt-hours of power, enough to power about 9,500 homes (Aoun Angueira, 2023).

Electric vehicle batteries are typically replaced when they reach 70 to 80 percent of their capacity, largely because the range they provide at that point begins to dwindle. Almost all of the critical materials inside them, including lithium, nickel, and cobalt, are reusable. A growing domestic recycling industry, supported by billions of dollars in loans from the Energy Department and incentives in the Inflation Reduction Act, is being built to prepare for what will one day be tens of millions of retired EV battery packs. The use of utility-scale battery storage is expected to increase from 1.5 gigawatts of capacity in 2020 to 30 gigawatts by 2025, and EV packs could provide a stockpile for that buildout. There are already at least 3 gigawatt-hours of decommissioned EV packs sitting around in the United States that could be deployed, and that the volume of them being removed from cars is doubling every two years. Using second-life batteries earns the same financial return as new grid-scale batteries at half the initial cost, and for now, repurposing the packs is more lucrative for automakers than sending them straight to recyclers. Until the recycling industry grows, it’s still quite expensive to recycle them. By selling or leasing retired packs to a grid storage company manufacturers can squeeze out more value out of them. B2U predicts only about 6 percent of decommissioned EV batteries in the U.S. will be used for grid-scale storage by 2027 (Aoun Angueira, 2023).

**SOLARCYCLE Recycling Company**

In a sign of times to come, SOLARCYCLE, a U.S. solar panel recycler headquartered in Texas, announced in 2023 a deal with EDF Renewables North America to recycle their solar panels that get damaged or broken during construction and operation from its grid-scale, distribution-scale, and onsite solar sites. EDF says it chose SOLARCYCLE as a preferred partner because the latter’s proprietary technology allows for the extraction of 95% of the value , from recycled panels, including silver, silicon, copper, aluminum, and glass. That’s at the high-achieving end of the current solar recycling industry standard – the US’s largest solar company, First Solar, says it can recover 90% of the value (Lewis, 2023).

**Redwood Materials, Battery Recycling Company**

In 2023 Redwood Materials, a battery recycling company, took on the decommissioning of a 4.6MWh stationary storage plant on the Hawaiian island of Kaua’i. From its base in northern Nevada, USA, Redwood’s mission is to create a circular supply chain for lithium-ion batteries, recycling materials from decommissioned batteries for use in new storage products. Redwood Materials mainly focuses on recycling batteries from electric vehicles, so this collaboration with Hawaii is a first step into the world of grid-scale battery recycling. The company is aiming to play a central role in the creation of a domestic supply chain for lithium-ion batteries products in the US, with ambitions to produce up to 100GWh worth of anode and cathode in materials in the US. Until now, much of the production of these critical materials has taken place in Asia. The reshoring of the supply chain will allow battery and automotive manufacturers to meet the stringent critical mineral and battery component requirements for consumers to qualify for EV tax credits introduced under President Joe Biden’s Inflation Reduction Act (Willis, 2023).

**Molten Sodium Batteries**

Both of these molten salt batteries use a molten sodium anode and a ceramic sodium-ion conducting solid state separator, usually β”-alumina (BASE [Beta Alumina Solid Electrolyte]), but their cathodes differ. Molten sodium battery systems use domestically abundant sodium metal anodes, ceramic ion conducting separators, and electrochemically active molten (or molten suspension) cathodes. However, molten sodium batteries operate at elevated temperatures, near 300°C, which results in relatively high cost due use of suitable battery materials. In grid-scale storage, molten sodium batteries provide rapid response times, hours-long discharge durations, deep cycle discharge, and long cycle lives over decades of low-maintenance use. They are suitable for load shifting, peak shaving, frequency regulation, renewables integration, voltage control, and backup power.[[5]](#footnote-4)

|  | Practical Energy Density(Wh/L) | Expected Cycle Life (cycles at 80% DOD) | Expected Operational Lifetime (years) | Operating Temperature (°C)  | Discharge Duration (at rated power) | Round-Trip efficiency |
| --- | --- | --- | --- | --- | --- | --- |
| NaS | 300-400 | 4,000-4,500 | 15 | 300-350 | 6-7 hours | 80% |
| $Na-NICl\_{2}$ | 150-190 | 3,500-4,500 | 20 | 270-300 | 2-4 hours | 80-85% |

*Table copied from* [*https://www.sandia.gov/app/uploads/sites/163/2022/02/ESHB\_Ch4\_Sodium\_Spoerke-1.pdf*](https://www.sandia.gov/app/uploads/sites/163/2022/02/ESHB_Ch4_Sodium_Spoerke-1.pdf)

1. Sodium-sulfur (NaS)- Developed in the 1960s. During the process of battery electrochemical cycling, NaS batteries oxidize and reduce sodium at the anode, while at the cathode the battery relies on the reversible reduction and oxidation of molten sulfur. During the discharge cycle, $Na^{+}$ is oxidized at the anode, travels through the ion conducting ceramic separator, and reacts with the molten sulfur (or polysulfides) reduced at the cathode, to produces molten polysulfides ($Na\_{2}S\_{5}$) that can be electrochemically cycled and oxidized back into elemental sulfur. Sodium-sulfur batteries are limited to approximately half their theoretical capacity because insoluble or solid polysulfides form at values of x < 3. However, since the reagent sulfur typically has low cost, the cathodes can be overbuilt to avoid capacity limitations. During discharge oxidation, we see sodium oxidation, sodium ion formation, and sodium ion migration.

xS + 2Na ↔ $Na\_{2}S\_{x}$ (3 ≤ x ≤ 5) $E\_{cell}$ ~ 2.08 V at 350 °C (1)

2Na + 4S → Na2S4 (2)

During a typical charge reaction in a sodium-sulfur battery, the molten polysulfides

($Na\_{2}S\_{5}$) at the cathode are oxidized back into sulfur, and sodium ions are reduced at the anode. Sodium ion deposition again occurs as the sodium ions (Na+) migrate from the cathode through the ceramic separator towards the anode where sodium ions gain electrons, and then the gained electrons reduce the sodium ions back into elemental sodium metal. During charge oxidation, we see electron transfer, sulfur formation, and sodium ion migration. Electrons are extracted from the polysulfide ions at the cathode, causing them to lose electrons. The oxidized sulfur species recombine to form elemental sulfur (S8). Simultaneously, sodium ions (Na+) migrate back from the cathode through the ceramic separator to the anode.[[6]](#footnote-5)

$Na\_{2}S\_{5}$ (molten) → 2Na+ + 5S (molten) + 2e- (3)

1. Sodium-nickel chloride (Na-Ni$Cl\_{2}$)- Developed in the 1970s. Also known as a sodium-metal halide battery, molten salt battery, salt battery, or ZEBRA battery (Zeolite Battery Research Africa Project), or Zero Emission Battery Research Activities. ZEBRA batteries and NaS batteries both rely on the oxidation and reduction of sodium at the anode and use a BASE separator, but sodium-nickel-chloride batteries (ZEBRA) also rely on the oxidation and reduction of the metal nickel at the cathode, not sulfur. In ZEBRA batteries, the cathode reaction is supported in a metal halide molten salt electrolyte, traditionally NaCl (sodium chloride) and AlCl3 (aluminum trichloride), which combine to form NaAl$Cl\_{4}$ (sodium tetrachloroaluminate).

Ni$Cl\_{2}$(s) + 2Na (l) ↔2 NaCl + Ni(s) $E\_{cell}$ ~ 2.58 V at 300 °C (4)

Li et al. (2016) write that as ZEBRA batteries do not retain liquid cathode chemistry, with the formation of both solid (nickel chloride-coated) nickel particles and solid sodium chloride particles, these batteries should be operated near 300°C to maintain high conductivity of the BASE separator and to ensure the molten state of the molten salt catholyte.[[7]](#footnote-6)

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1. Sodium-iron chloride ($NaFeCl\_{2}$)- The Inlyte team has achieved long-duration energy storage by replacing nickel with iron in order to achieve cost reductions while maintaining high performance. Sodium-iron chloride battery research to date has shown variable cycling performance in terms of the number of charge-discharge cycles it can complete before losing performance (Maisch, 2024A).

**Sodium-ion Batteries**

Like lithium-ion batteries, sodium-ion batteries operate at room temperature and employ a transition metal cathode, a non-selective, electrically insulating porous polymer separator, a carbon or a titanate anode, and an organic or aqueous liquid electrolyte. To cycle the battery, sodium ions are alternately intercalated into the cathode during discharge and the anode during charge. The separator is the part of the battery that serves to prevent physical contact and electrical shorting between anode and cathode, and both sodium-ion and lithium-ion batteries use porous polymer materials for the separator, unlike molten sodium batteries which use solid state materials for the separator.[[8]](#footnote-7)

So how is a sodium-ion battery constructed? Like a lithium-ion cell, there are five integral parts of a Li-ion cell–the separator, electrolyte, current collectors, negative electrode, and positive electrode.The most common components of a sodium-ion battery positive electrode are transition metal oxides, polyanionic compounds, and Prussian blue analogues; with the general formula for transition metal oxides being NaxMO2, where "M" is a transition metal like Ni, Mn, Fe, or Co, signifying that the cathode material primarily consists of a layered structure of sodium ions and transition metal ions within an oxygen lattice. Like lithium-ion batteries, the negative electrode is typically composed of graphite. The most widely used salts in non-aqueous electrolytes are sodium perchlorate ($NaClO\_{4}$) and sodium hexafluorophosphate ($NaPF\_{6}$) dissolved in a mixture of these solvents. Aluminum and copper are the most commonly used current collectors for the positive electrode and negative electrode.

Integration of sodium-ion batteries into the battery use profile could lead to lower costs, less fire risk, and less need for lithium, cobalt, and nickel, as these precious metals carry an environmental damage risk in their mining. Manganese and iron could be substituted for cobalt and nickel. Advantages of sodium batteries include cost, as sodium is abundant on the Earth and easy to mine. This abundancy leads to lower environmental risks, such as mining. The wider availability of sodium leads to supply chain stability for countries like the U.S., who currently rely on China for lithium processing. Sodium batteries also have lower energy density, and consequently less risk of fire when damaged, or a concept known as thermal runaway. Disadvantages of sodium batteries include their lower energy density, as they produce less electricity per unit of mass, so you need more sodium and a larger battery, which makes sodium batteries more suitable for grid-scale storage applications. One of the challenges with sodium batteries is getting salt to hold up under repeated cycles of charging and discharging, including improving charging speed and battery range. Sodium is cheaper than lithium, by some estimates by a degree of nearly 50 times, and can even be harvested from seawater.

Advantages of sodium batteries over lithium batteries include better performance in cold weather and reduced risk of fire. Sodium-ion batteries outperform lithium-ion batteries in extreme cold, as CATL, a Chinese company, has said its new battery works in temperatures as low as -40° Fahrenheit. Conversely, lithium-ion cells have a more mild mercury range for typical batteries at between 60 degrees and 110 degrees. It has been reported by Scientific American that at 20 degrees Fahrenheit, an EV's driving range drops by about 12%. As for reduced risk of fire, when lithium-ion batteries sustain damage, it can lead to “thermal runaway,” which triggers a dangerous and toxic fire. Sodium-ion batteries also have a wider temperature range without degradation, meaning they last longer. Thermal runaway and fire risk is not the only reason sodium-ion batteries are considered safer than lithium-ion batteries, as they use less volatile electrolytes and different oxides for the cathode. Some sodium-ion batteries can also be fully discharged, allowing for safer transportation of the battery system. Sodium-ion cathodes also generally do not use cobalt or nickel, like many lithium-ion systems do, which are minerals that are expensive to mine and procure. Also, whereas lithium-ion batteries typically use graphite for the carbon anode, sodium-ion batteries more commonly use amorphous “hard carbon.”[[9]](#footnote-8)

The major disadvantage of sodium batteries is their low energy density compared to lithium-ion as an EV running on a sodium-ion battery will go fewer miles per charge than a lithium-ion battery of the same size. A typical sodium-ion battery has an energy density of about 150 watt-hours per kilogram at the cell level, whereas lithium-ion batteries can range from about 180 to nearly 300 watt-hours per kilogram. The sodium ion is larger as compared to the lithium ion, which leads to a slightly smaller reduction potential of sodium, and thus a lower energy density, though this lower energy density can be accommodated for by different degrees of ion intercalation and battery engineering.

As for production, the sodium-ion batteries manufacturing process is similar to that of lithium-ion batteries, or at least similar enough that companies can shift existing assembly lines without having to spend heavily on retooling. In 2024, global production of lithium-ion batteries was about 1,500 gigawatt-hours, and production of sodium-ion batteries was 11 gigawatt-hours, or less than 1 percent, according to Benchmark Mineral Intelligence. However, sodium-ion battery production is growing and is projected to reach 140 gigawatt-hours by 2030, about 13 times its current level, according to Benchmark. Lithium-ion production also is projected to nearly triple by 2030. Cost competitiveness for sodium-ion batteries is a challenge in 2024 because lithium prices are unusually low, as the global supply of lithium has grown more quickly than demand since 2022, leading to lower prices.

Some reports suggest that sodium-ion batteries might have a cost advantage over lithium-ion in the long run, with McKinsey and Co. reporting in 2023 that sodium-ion batteries have the potential to be 20 percent less costly than lithium-ion batteries. Stackable sodium-ion batteries could be used in grid-scale applications, or stationary energy storage applications, which can accommodate a larger infrastructure due to their lower energy density. The lower energy density of sodium-ion batteries compared to lithium-ion that makes them less of a thermal runaway risk also means you need more volume to achieve the same storage capacity. Utility-scale storage systems can be spread over acres, while mobile or portable storage applications, like EVs and laptops can not (Puttré, 2024).

***Increasing the Energy Density in Sodium-ion Batteries***

To increase the energy density of a sodium battery, researchers are focusing on optimizing electrode materials by using nanostructured designs, incorporating high-capacity cathode materials like Prussian Blue analogues, improving electrolyte conductivity, minimizing interfacial resistance, and tailoring the morphology of the anode (often hard carbon) to facilitate efficient sodium ion diffusion within the electrode structure. Cycling stability must be maintained while increasing energy density. Potential safety issues related to sodium battery chemistry include thermal stability and electrolyte flammability.

To improve the cathode in sodium-ion batteries, high-voltage materials could be used, the surface could be modified, or you could use nanostructuring. Cathode materials with higher operating voltage like polyanion-based compounds or layered transition metal oxides could be used. The surface of cathode particles could be engineered with coatings to improve stability and reduce side reactions. Nano-sized cathode particles could be designed to increase the surface area for faster charge transfer. To optimize the anode in sodium-ion batteries, hard carbon modifications are needed, alloying materials should be used, and you should use pre-sodiation techniques. You can tailor the pore structure of hard carbon anodes to optimize sodium storage capacity and diffusion kinetics. Metal alloys with high sodium storage potential can be used, such as sodium-tin or sodium-antimony alloys. Pre-sodiation is pre-treating the anode with sodium ions to improve initial cycling stability. Electrolyte engineering factors to consider when improving sodium-ion batteries include: solvent selection, use of salt additives, and use of solid-state electrolytes. It is important to choose appropriate solvents with high ionic conductivity and good compatibility with electrode materials. Incorporating salt additives to the electrolyte enhances ion transport and stabilizes the electrode interfaces. Solid-state electrolytes have the potential for improved safety and higher energy density. Structural design options to optimize sodium-ion batteries include compaction and electrode architecture. Electrode loading can be increased by optimizing the electrode compaction process to pack more active material per unit volume. As for electrode architecture, porous electrode structures can be designed to facilitate ion diffusion and minimize internal resistance.[[10]](#footnote-9)

***Optimizing Electrolyte Performance in Sodium-ion Batteries***

To optimize electrolyte performance in a sodium battery, common minerals considered include sodium salts like sodium perchlorate (NaClO4), sodium hexafluorophosphate (NaPF6), and sodium trifluoromethanesulfonate (NaCF3SO3), often dissolved in organic solvents like ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), and diethyl carbonate (DEC), with the specific choice depending on desired properties like conductivity, stability, and compatibility with the electrode materials. To optimize sodium-ion battery electrolytes, salt, solvent and additive selection is important, as is considering the ionic conductivity, electrochemical stability, and thermal stability of the minerals.

Salts which could be used for the electrolyte include: 1) NaPF6, which is widely used due to good conductivity and stability, but can be sensitive to moisture 2) NaClO4, which offers high conductivity and good compatibility with various cathode materials, and 3) NaCF3SO3, which may provide improved stability at high temperatures. Solvents which could be selected for the electrolyte include: 1) Ethylene carbonate (EC), which has high polarity, good solvation for sodium ions, but can form a thick SEI layer 2) Propylene carbonate (PC), which has moderate polarity, good conductivity, often mixed with EC 3) Dimethyl carbonate (DMC), which has lower viscosity, can improve rate performance when added in mixtures, and 4) Diethyl carbonate (DEC), which has low viscosity, can enhance cycle life. Additives which could be used to synthesize electrolytes in sodium-ion batteries include: 1) Fluoroethylene carbonate (FEC), which can help form a stable SEI layer on the anode, improving cycle life, and 2) Sulfur-based additives, which can modify the cathode electrolyte interphase (CEI) for better performance. When choosing minerals for sodium battery electrolytes, you should consider: 1) Ionic conductivity, the ability of the electrolyte to conduct sodium ions efficiently 2) Electrochemical stability, the voltage range at which the electrolyte remains stable without decomposition 3) Compatibility with electrodes, the electrolyte should not react excessively with the anode and cathode materials, and 4) Thermal stability, the electrolyte should maintain its properties over a wide temperature range.[[11]](#footnote-10)

***Literature Review***

Sekine et al. (2024) have developed a machine learning model to identify the optimum composition to attain the highest energy density for sodium-ion batteries. Sodium-containing transition-metal layered oxides (NaMeO2) are powerful materials for the positive electrodes of Na-ion batteries, which offer exceptional energy density and capacity. However, for multi-element layered oxides composed of several transition metals, the number of possible combinations makes finding the optimal composition extremely difficult, as even minor changes in the selection and proportion of transition metals can bring about marked changes in crystal morphology and can affect battery performance. The Japanese researchers, however, claim to have identified Na[Mn0.36Ni0.44Ti0.15Fe0.05]O2 as the optimum composition for the highest energy density, one of the most important characteristics in electrode materials (Sekine, et al., 2024).

A new chemical composition has emerged for sodium batteries, sodium vanadium phosphate [NaxV2(PO4)3]. By adding vanadium to the chemical mix, sodium ions in the new formula can move about more efficiently during charge/discharge cycles. U.S. researchers at the Canepa Lab in Houston were able to raise the energy density of the sodium battery by more than 15%, up to an energy density of 458 watt-hours per kilogram (Wh/kg) compared to the 396 Wh/kg in older sodium-ion batteries. The researchers created a battery prototype using the new material, NaxV2(PO4)3, demonstrating significant energy storage improvements. NaxV2(PO4)3, part of a group called "Na superionic conductors" or NaSICONs, is designed to let sodium ions move smoothly in and out of the battery during charging and discharging. The key to the sodium vanadium battery, vanadium, can maintain its stability in different states, which explains why it is commonly used in flow batteries. The Canepa Lab created a continuous voltage of 3.7 volts, while remaining stable while charging and discharging, compared to 3.37 volts for older sodium batteries. Continuous voltage change is a key feature, which means that the battery can perform more efficiently without compromising the electrode stability (Park et al., 2024; Casey, 2024B).

In the race to create batteries, with high energy and high power density, Korean researchers have developed a hybrid sodium-ion battery which improves the slow energy storage of anodes, and enhances the low capacity of supercapacitor-type cathode materials. This new battery blends a greater energy density than lithium-ion batteries (247 Wh/kg) with the supercapacitors' power density (34,748 W/kg). The researchers believe that it could be suitable for rapid charging applications ranging from electric vehicles to smart electronic devices and aerospace technologies. This hybrid battery utilizes two distinct metal-organic frameworks for optimized synthesis. The anode material with improved kinetics was created through the inclusion of fine active materials in porous carbon derived from metal-organic frameworks, and the high-capacity cathode material was synthesized, with the combination of the cathode and anode materials allowing for the development of a sodium-ion storage system optimizing the balance and minimizing the disparities in energy storage rates between the electrodes (Choi et al., 2024; KAIST, 2024).

Netherlands researchers produced a sodium-ion battery with the negative electrode, the anode, made from organic materials, hard carbon, and containing no cobalt, while the cathode, positive electrode, is high-voltage and layered cathode. This battery is high energy and fast charging, at 9 minutes and 3,000 cycles (Vasileiadis et al., 2024; Kazmer, 2024). Japanese researchers have developed a solid-state sodium battery, which uses a mass synthesis process for sodium-containing sulfides electrolytes with high sodium ion conductivity, about 10 times higher than required for practical use, and glass electrolyte with high formability and reduction resistance, which is key to the practical use of all-solid-state sodium batteries. For the synthesis process, they used sodium polysulfides (sulfides with two or more atoms of sulfur) as both the material and the flux, which promotes fusion. This process is useful for the production of almost all sodium-containing sulfide materials, including solid electrolytes and electrode active materials (Nasu et al., 2024; Westenhaus, 2024A).

**Sodium for Heat Storage**

Currently, heat is produced by burning fossil fuels such as coal, oil, and gas, but that will need to change as the world shifts to clean energy. We need to develop more efficient heating systems that do not rely on fossil fuels, and Barbosa and Menon (2024) have developed a salt system that could be used for heating buildings or integrated with a heat pump to cool buildings. A basic reversible chemical reaction is the foundation for their approach: A forward reaction absorbs heat and then stores it, while a reverse reaction releases the heat, enabling a building to use it. Each salt molecule can hold a certain number of water molecules within its structure. To instigate the chemical reaction, the researchers dehydrate the salt with heat, so it expels water vapor as a gas. To reverse the reaction, they hydrate the salt with water, forcing the salt structure's expansion to accommodate those water molecules (Barbosa and Menon, 2024).

As this expansion/contraction process happens, the salt gets more stressed and will eventually mechanically fail, the same way lithium-ion batteries only have so many charge-discharge cycles. Magnesium chloride often fails because it absorbs too much water, whereas strontium chloride is very slow to hydrate. Together, their respective limitations can mutually benefit each other and lead to improved heat storage. The next step is developing the structures capable of containing these salts for heat storage, which is the focus of an Energy Earthshots project. A system-level demonstration is also planned, where one solution is filling a drum with salts in a packed bed reactor. Then hot air would flow across the salts, dehydrating them and effectively charging the drum like a battery. To release that stored energy, humid air would be blown over the salts to rehydrate the crystals. The subsequently released heat can be used in a building instead of fossil fuels. While initiating the reaction needs electricity, this could come from off-peak (excess renewable electricity) and the stored thermal energy could be deployed at peak times.

**Lithium-ion Batteries**

While all considered "lithium batteries," the key difference lies in their electrolyte composition: lithium-ion batteries use a liquid electrolyte, lithium polymer batteries use a gel-like polymer electrolyte, and lithium metal batteries use pure metallic lithium as the anode, making them non-rechargeable (primary batteries) with a significantly higher energy density compared to the other two types. Nickel is used to increase the energy density of the battery. Cobalt is used to stabilize the energy density of the battery, and is mined in the DR Kongo. We also want to strive to use more manganese over cobalt, as manganese is a widely abundant resource and a safer alternative than a battery packed with high concentrations of nickel. We want to Increase manganese, get rid of the cobalt and decrease nickel content.

Lithium-ion batteries have been the workhorse for electric batteries for several since the 1990s, and there are several types of these batteries, as discussed below. Lithium is the primary choice for mobile applications such as electric vehicles and portable devices, however, lithium batteries are less attractive for grid-scale energy storage due to its higher costs and environmental mining impact. Advantages of lithium-ion batteries include high energy density, high power, high efficiency, and low self-discharge. A lithium-ion battery uses intercalated lithium compound instead of metallic lithium as its electrode, unlike the disposable lithium primary battery. Lithium-ion batteries do not require complete discharge before recharging, and can handle many charge/discharge cycles.

So how is a lithium-ion battery constructed? Like a sodium-ion cell, there are five integral parts of a Li-ion cell–the separator, electrolyte, current collectors, negative electrode, and positive electrode. In a lithium-ion battery, the positive electrode is a lithium metal oxide, and the negative electrode is graphite. The electrolyte is composed of a lithium salt (e.g. $LiPF\_{6}$) in a mixture of organic solvents (e.g. ethylene carbonate [EC] and dimethyl carbonate [DMC]). Aluminum and copper are the most commonly used current collectors for the positive electrode and negative electrode. As with a sodium-ion battery, the separator membrane is located between the electrodes to prevent physical contact without compromising the flow of lithium ions. The liquid electrolytes most often used in lithium-ion batteries are microporous polymer membranes. The microporous polymer membranes may be made of polyethylene (PE), polypropylene (PP), or combinations of both (PP/PE/PP). The combination PP/PE/PP is a multilayer separator known as the “shutdown separator.”[[12]](#footnote-11)

Current research involves increasing lifetime and energy density, and improving the safety profile.

***Lifetime***

Aging is caused largely by parasitic reactions at the electrodes during calendar aging and cycle aging. Calendar aging refers to battery degradation that occurs when a battery is simply sitting idle, not being actively charged or discharged, and is primarily influenced by factors like temperature and state of charge (SOC) during storage. Cycle aging refers to battery degradation that happens during each charge-discharge cycle, and is affected by factors like the depth of discharge (DOD) and current rate. Aging is linear for most cycling conditions from around 80% capacity to 60% capacity.[[13]](#footnote-12) New electrolyte formulations represent one area of research to attain longer lifetimes, with different formulations optimized for different conditions, such as temperature or charging rate.

***Energy Density***

Grid energy storage applications have a lower energy density requirement than that for EV , and commonly sees the use of LFP cells, which are safer than metal oxide positive electrodes. Higher energy densities can be achieved both by cell-level materials and module to system-level balance-of-plant modifications. In Li-ion batteries, positive electrodes with higher nickel content could be used to increase energy density due to the correlation between large Ni content and greater intercalation of lithium ions. As for promising negative electrode materials for Li-ion batteries, silicon has a high theoretical capacity of 4200 mAh $g^{-1}$. However, silicon undergoes a 400% volumetric change during lithium intercalation/de-intercalation, which could cause other structural issues such as self-pulverization and fracture that ultimately lead to loss of electrochemical contact. Different electrolytes, merging graphite with silicon, and designing different silicon structures could solve this silicon volume change issue. Higher energy densities can also be achieved with solid state batteries. In a lithium solid state battery, the organic liquid electrolyte is replaced with a solid-state electrolyte, which enables the use of Li metal negative electrodes in place of graphite. Higher energy densities can also be achieved using non-cylindrical cells, making individual modules larger, and minimizing the space between larger units (either by eliminating the servicing aisle in intermodal containers or minimizing the distance between cabinet-based systems).[[14]](#footnote-13)

***Thermal Runaway***

Thermal runaway of the cell occurs when chemical and electrical energy is released from batteries with high energy density operated under not recommended conditions, and heat is generated faster than it can be dissipated, leading to fire, smoke, and particulate ejecta. Thermal runaway is more common in Li-ion batteries using metal oxide positive electrode materials, which possess fuel, oxygen, and an ignition source, potentially leading to combustion or explosion if thermal runaway occurs. The fuel is the organic electrolyte, which is unstable at elevated temperatures and easily ignited once it is exposed to air, with the positive electrode releasing oxygen once it is exposed to elevated temperatures during thermal runaway.[[15]](#footnote-14)

A single-crystal electrode design in electric batteries could increase the longevity and range of electric vehicles, and also help integrate renewable energy sources into power grids. Canadian researchers have developed a lithium-ion battery with a single crystal electrode. They studied two types of lithium-ion batteries, one with a regular electrode and the other with a single crystal electrode under the ultrabright synchrotron light at CLS. Inside a regular battery, lithium forces atoms of the electrode material to expand and contract, leading to microscopic cracking. However, the battery with a single crystal electrode showed no such signs of cracking. The difference between the two battery electrodes is in the shape and behavior of their materials. The electrode of a regular battery comprises particles that are about 50 times thinner than human hair, with these particles composed of much smaller crystals and are held together like snowflakes in a snowball. On the other hand, the single crystal electrode is like a big ice cube, which is much more resistant to stress and strain (Bond, 2024). XNO materials are based on proprietary mixed niobium oxide compositions and microparticle designs and enable lithium-ion batteries to safely fast charge in less than 10 minutes, maintain high energy densities even at extreme temperatures, and deliver high-power across a cycle life of more than 10,000 cycles (Foley, 2024).

**Lithium Polymer (Li-Po)**

Also known as Li-Po batteries, or lithium-ion polymer batteries, these batteries use a polymer electrolyte instead of a liquid electrolyte, giving them a high energy density. This is a battery with a soft polymer casing and soft external pouch for the lithium-ion battery inside. Due to their soft shells, Li-Po batteries are lighter and more flexible than other lithium-ion batteries. Li-Po batteries perform better in high temperatures than LIBs, because they can handle larger charge/discharge currents with more stability. Li-Po batteries may be used in devices such as very thin laptop computers, video game consoles, electronic cigarettes, wearables, drones, and portable media players where small form factors are considered. Li-Po batteries are safer from explosion than lithium-ion batteries, and have a longer life span due to not losing its charging capacity as fast. Li-Po batteries cost almost double that of LIBs, and can still catch fire if punctured.[[16]](#footnote-15)

**Lithium Metal Batteries**

Rechargeable lithium metal batteries are an alternative to lithium-ion batteries used in electric vehicles and energy storage applications that require high energy density. Challenges to lithium metal batteries include safety concerns and a shortened battery cycle life arising from a combination of undesirable lithium dendrite and solid-electrolyte interphase formations. Chinese researchers have developed a new generation of lithium metal batteries based on microcrack-free polymer electrolytes, which promise extended lifespan and enhanced safety at temperatures as high as 100 degrees Celsius. The microcrack-free polymer electrolytes are synthesized via a straightforward one-step click reaction, exhibiting notable attributes including “a remarkable resistance to dendrite growth and outstanding non-flammability,” the researchers reported. By comparison, the cycling performance of conventional liquid electrolyte lithium metal batteries is fewer than 10 cycles at high temperatures (Maisch, 2024B).

**Lithium-Iron-Phosphate (LFP)** ($LiFePO\_{4}$)

In a lithium iron phosphate (LFP) battery, the cathode is composed of phosphate, and the anode is a graphitic carbon. LFP batteries are the most common type of lithium battery for replacing lead-acid deep-cycle batteries, because LFP battery cells have a nominal voltage of 3.2 volts, so connecting four of them in series results in a 12.8-volt battery. Lithium iron phosphate batteries are one of the most popular options for applications requiring a large amount of power, as they have the benefit of durability, a long life cycle, and safety. LFP batteries last up to 2,000 cycles, and unlike lead-acid batteries, depth of discharge has a minimal impact on the lifespan of LFP batteries. Most LFP batteries are rated at 80% depth of discharge, and some even allow 100% discharging without damaging the battery. Disadvantages of LFP batteries include that they have a relatively low specific energy, and their performance can also suffer in low temperatures.[[17]](#footnote-16)

**Lithium Cobalt Oxide (LCO)** ($LiCO\_{2}$**)**

Lithium cobalt oxide (LCO) batteries are the most common type of lithium-ion battery, and use a carbon-based anode and lithium cobalt oxide as the cathode. Lithium cobalt oxide (LCO) batteries are used in cell phones, laptops, tablets, digital cameras, and many other consumer-facing devices. They have high specific energy but low specific power, which means that they do not perform well in high-load applications, but they can deliver power over a long period. Current research aims to replace expensive cobalt with more abundant transition metals. LCO positive electrodes are not employed in grid energy storage applications. LCO batteries have high specific energy, which means they can deliver power over a relatively long period under low-load applications. In addition to cobalt being expensive, LCO batteries also have a short lifespan, usually between 500-1,000 cycles. Other disadvantages of LCO batteries include low thermal stability, which leads to safety concerns, and a low specific power, which limits the ability of LCO batteries to perform in high-load applications.[[18]](#footnote-17)

**Lithium Manganese Oxide (LMO)** ($LiMn\_{2}O\_{4}$)

Lithium Manganese Oxide (LMO) batteries use LMO as the cathode material and graphite as the anode. LMO batteries have a three-dimensional structure that improves ion flow, lowers internal resistance, and increases current handling while improving thermal stability and safety. Devices which use LMO batteries include portable power tools, medical instruments, and some hybrid and electric vehicles. Advantages of LMO batteries include quick charging and high specific power, which means that they can deliver higher current than LCO batteries. LMO batteries also offer better thermal stability than LCO batteries, meaning they can operate safely at higher temperatures. One other benefit to LMO batteries is their flexibility. Tuning the internal chemistry allows LMO batteries to be optimized to handle high-load applications or long-life applications. LMO batteries, however, have a short lifespan, typically lasting only 300-700 charge cycles.[[19]](#footnote-18)

**Lithium Nickel Manganese Cobalt Oxide (NMC)** ($LiNi\_{x}Mn\_{y}Co\_{1-x-y}O\_{2}$)

Lithium nickel manganese cobalt oxide (NMC) batteries include three main elements in the cathode: nickel, manganese, and cobalt, for a battery that is stable with a high specific energy. When combined together, we get benefits of each element. For example, nickel on its own has high specific energy but is not stable, while manganese is exceptionally stable but has a low specific energy. NMC batteries are used in similar applications as LMO batteries, such as power tools, electronic powertrains for e-bike, scooters, and some electric vehicles. NMC batteries benefit from high energy density and a longer lifecycle at a lower cost than cobalt-based batteries, while also being safer than LCO batteries due to their higher thermal stability. However, NMC batteries do have a drawback, in that they have a slightly lower voltage than cobalt-based batteries.[[20]](#footnote-19)

**Lithium Nickel Cobalt Aluminium Oxide (NCA)** ($LiNi\_{0.80}Co\_{0.15}Al\_{0.05}O\_{2}$)

Lithium nickel cobalt aluminum oxide (NCA) batteries use nickel, cobalt, and aluminum as the cathode, and graphite as the anode. They have high specific energy with decent specific power and a long lifecycle, which means they can deliver a relatively high amount of current for extended periods. Tesla and other electric vehicle manufacturers use NCA batteries, as they have the ability to perform in high-load applications with high energy with a long battery life. Disadvantages to NCA batteries include that the batteries aren’t as safe as most other lithium technologies and are more expensive.[[21]](#footnote-20)

**Lithium Titanate (LTO)** ($Li\_{4}Ti\_{5}O\_{12}$)

Lithium titanate (LTO) batteries utilize lithium titanate in the anode instead of graphite, with LMO or NMC as the cathode. LTO batteries are extremely safe with a long lifespan that charges faster than any other lithium battery type. An LTO battery has less capacity than graphite anodes, but are more stable during lithiation/delithiation and can sustain tens of thousands of cycles. Some of the applications that use LTO batteries include electric vehicles and charging stations, uninterrupted power supplies, wind and solar energy storage, solar street lights, telecommunications systems, and aerospace and military equipment. Advantages of LTO batteries include fast charging, an extremely wide operating temperature, a long lifespan, and superb safety because of their stability. However, LTO batteries are expensive and have low energy density, which means they store a lower amount of energy relative to its weight when compared to some other lithium technologies.[[22]](#footnote-21)

**Lithium-Sulfur Batteries**

<https://pmc.ncbi.nlm.nih.gov/articles/PMC9060784/>

Timer, John (2025) Ars Technica, A solid electrolyte gives lithium-sulfur batteries ludicrous endurance, <https://arstechnica.com/science/2025/01/a-solid-electrolyte-gives-lithium-sulfur-batteries-ludicrous-endurance/>

Song, H., Münch, K., Liu, X. et al. (2025) All-solid-state Li–S batteries with fast solid–solid sulfur reaction, Nature, <https://doi.org/10.1038/s41586-024-08298-9>

Sulfur is abundant and cheap, and sulfur atoms are lighter compared (32 u)to many of the other materials used in battery electrodes, such as manganese (55 u), nickel (59 u), or cobalt (59 u).

The bulk of the material used in modern electric batteries is in the electrodes, where the lithium or sodium gets stored when the battery isn't charging or discharging. To make lighter and more compact electric batteries is to find electrode materials that can store more lithium or sodium, such as by incorporating silicon into the electrode materials. Sulfur can store more lithium or sodium than silicon, but a drawback to sulfur is that it has a tendency to react with itself, producing ions that can float off into the electrolyte. Electrode materials tend to expand in proportion to the amount of lithium or sodium that gets stored, which can create physical strains on the battery's structure.

Sodium-sulfur batteries only work at temperatures high enough to melt both of these components. Lithium-sulfur batteries operate in a similar manner to lithium-ion batteries. The performance of lithium-sulfur batteries has tended to degrade rapidly.

The elemental sulfur used as an electrode is a very poor conductor of electricity, so it has to be dispersed within a mesh of conductive material. Conversely, graphite both stores lithium or sodium and conducts electricity relatively well, as graphite is composed of countless sheets of graphene. In a lithium-sulfur battery, lithium is stored in the electrode as Li2S, which occupies more space than the elemental sulfur it's replacing. In a sodium-sulfur battery, sodium is stored at the negative electrode (anode) as elemental sodium metal, and during discharge, it reacts with sulfur at the positive electrode (cathode) to form sodium polysulfides, primarily existing as Na2S4 and Na2S8 compounds depending on the state of charge.

One challenge to lithium-sulfur batteries is the relatively slow chemical reaction between lithium ions and elemental sulfur, which has an eight-atom ring, which prevents fast charging. Lithium-sulfur batteries have a short life-span due to the formation of inactive intermediate products, semi-stable intermediates with smaller chains of sulfur, during the reaction of lithium and sulfur at the electrode. These sulfur intermediates are soluble in most electrolytes, allowing them to travel to the opposite electrode and participate in chemical reactions there, which leads to battery discharge without allowing the electrons to be put to use. This process of intermediate sulfur formation gradually leaves the electrode's sulfur unavailable for participating in future charge/discharge cycles.

A solution to the problem of lithium-sulfur reaction intermediates dissolving in most electrolytes is to use solid electrolytes in a solid-state battery. Solid electrolytes are materials that have a porous structure at the atomic level, with the environment inside the pores being favorable for ions. This allows ions to diffuse through the solid. If there's a way to trap ions on one side of the electrolyte, such as a chemical reaction that traps or de-ionizes them, then it can enable one-way travel. Critically, pores that favor the transit of lithium ions, which are quite compact, aren't likely to allow the transit of the large ionized chains of sulfur.

The researchers began by testing a glass formed from a mixture of boron, sulfur, and lithium (B2S3 and Li2S). But this glass had terrible conductivity, so they started experimenting with related glasses and settled on a combination that substituted in some phosphorus and iodine. The iodine turned out to be a critical component. While the exchange of electrons with sulfur is relatively slow, iodine undergoes electron exchange (technically termed a redox reaction) extremely quickly. So it can act as an intermediate in the transfer of electrons to sulfur, speeding up the reactions that occur at the electrode. In addition, iodine has relatively low melting and boiling points, and the researchers suggest there's some evidence that it moves around within the electrolyte, allowing it to act as an electron shuttle.

**Solid-State Batteries**

Current research into solid-state batteries includes improvements in safety and energy density. However, solid-state batteries still suffer from high production costs, complex manufacturing processes, and a lack of a mature supply chain. Semi-solid-state batteries have been deployed in electric vehicles, and they have already reached GWh-level scale installation, with cell energy densities ranging from 300–360 Wh/kg, according to TrendForce. There are three methods of constructing solid-state batteries based on different types of electrolytes. Polymer-based solid-state batteries must improve their voltage tolerance and ionic conductivity. The most chemically stable class of solid-state batteries use oxide solid-state electrolytes, but these are difficult to manufacture, as the “solid-solid” contact between the electrolyte and the cathode/anode active materials leads to higher internal resistance. Sulfide-based solid-state batteries have strong ionic conductivity, which is close to that of liquid electrolytes. However, sulfide solid-state batteries can be unstable in air and highly sensitive to moisture, adding complexity to the production process and potentially releasing H2S gas, which is poisonous as well as flammable (Maisch, 2024C). Toyota is making solid-state batteries with lithium sulfides, where the sulfides that will be chemically transformed into lithium sulfides are byproducts of petroleum refining (O’Neil, 2024). U.S. researchers have developed a solid-state battery which uses a ceramic electrolyte separator, which was tested without compression and showed no signs of swelling or volume change. According to ION, the battery will not require compression, swell budget, an extensive cooling system, or heavy fire barriers (Rayner, 2024).



*Image: Trendforce*

*Maisch, Marija (2024) PV Magazine, Solid-state batteries enter pilot production, costs expected to drastically drop,*

[*https://www.pv-magazine.com/2024/11/01/solid-state-batteries-enter-pilot-production-costs-expected-to-drastically-drop/?utm\_source=Global+%7C+Newsletter&utm\_campaign=2c91113505-dailynl\_gl&utm\_medium=email&utm\_term=0\_6916ce32b6-2c91113505-160603208*](https://www.pv-magazine.com/2024/11/01/solid-state-batteries-enter-pilot-production-costs-expected-to-drastically-drop/?utm_source=Global+%7C+Newsletter&utm_campaign=2c91113505-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-2c91113505-160603208)

Solid-state lithium batteries could attain significantly higher gravimetric and volumetric energy densities than lithium-ion batteries of more than 500 $Wh/kg^{-1}$ and 1,000 $Wh/l^{-1}$, respectively. Zero-lithium-excess based solid state batteries face the challenge of active lithium loss and coulombic efficiency penalty, which is caused by an inhomogeneous lithium plating that can occur while the batteries are charged and discharged, which can reduce their efficiency and overall performance. Thin, dense lithium metal foils, produced via thermal evaporation, or excess lithium could be used to limit the loss of lithium in these batteries, however, using excess lithium adversely impacts the batteries' energy density (Burton et al., 2024; Fadelli, 2024).

Tohoku University (2024) SciTechDaily, The Battery Breakthrough That Could Transform Electric Vehicles and Renewable Energy,

<https://scitechdaily.com/the-battery-breakthrough-that-could-transform-electric-vehicles-and-renewable-energy/>

Muzakir, M., Manickavasakam, K., Cheng, E.J., et al. (2024) Inorganic solid electrolytes for all-solid-state lithium/sodium-ion batteries: recent developments and applications, Journal of Materials Chemistry A, <https://pubs.rsc.org/en/content/articlelanding/2025/ta/d4ta06117a>

By developing new materials, improving synthesis methods, and overcoming compatibility issues, current efforts are driving innovation toward practical ASSBs that could transform how we store and use energy. Inorganic solid electrolytes (ISEs), such as oxides, sulfides, hydroborates, antiperovskites, and halides, can be used in ASSBs, with these materials not only utilized as electrolytes but also serve as catholytes and interface layers, which improve both battery performance and safety. Precise tuning is crucial for developing batteries with higher energy densities, longer life cycles, and better safety profiles than conventional liquid-based batteries. Key electrochemical characteristics of ISEs include ionic conductivity, stability, and compatibility with electrodes. Challenges remain in the development of ASSBs, including the limited compatibility between ISEs and electrodes, which can lead to harmful interfacial reactions (Muzakir et al., 2024: Tohoku University, 2024).

**Solid-State Lithium Batteries**

U.S. researchers have developed a solid-state lithium-air battery (SS-LAB) which uses a four-electron reaction at room temperature, achieving a higher energy density. Previous lithium-air designs utilize a chemical reaction for lithium superoxide or peroxide, which involves one or two electrons stored per oxygen molecule, whereas the new cell produces lithium oxide, which can hold four. The new design can also operate with oxygen supplied by air from the surrounding environment, thus eliminating the need for oxygen tanks. SS-LAB technology could power wearable technology, unmanned aerial systems, electric vehicles, personal electronics, and heavy-duty transportation. Lithium-air batteries have the highest projected energy density of any battery technology being considered for the next generation of batteries beyond lithium-ion (Maisch, 2024E).

Paleja, Ameya (2024) Interesting Engineering, Korea unleashes fire-proof EV battery that holds 87% power after 1000 cycles,

<https://interestingengineering.com/energy/korea-unleashes-fire-proof-ev-battery-that-holds-87-power-after-1000-cycles>

Lim, H., Chae, M.S., Jamal, H. et al. (2024) Triple-Layered Noncombustible PEO-Based Solid Electrolyte for Highly Safe Lithium-Metal Batteries, Small, 2406200, <https://doi.org/10.1002/smll.202406200>

Korean researchers have developed a triple-layer solid polymer electrolyte containing a lithium-ion battery that can extinguish itself if it catches fire and is resistant to explosion. Solid-state batteries perform relatively poorly than their liquid polymer counterparts since achieving complete contact between the electrodes and electrolytes is difficult. As a battery undergoes charging and discharging during its usage, lithium-ions form sharp metallic dendrites or tree-like structures. Not only do these dendrites cause a loss of battery performance, but they also increase the risk of fire and explosion. Each layer of the electrolyte performs a specific function. A robust middle layer made from zeolite provides strength to the structure. In contrast, the softer outer layers deliver electrode contact and improve battery performance and efficiency. On one side is decabromodiphenyl ethane (DBDPE), which prevents fires and can also extinguish one if it occurs, while high concentration salt of lithium bis (trifluoromethane sulfonyl) imide) (LiTFSI) allows faster movement of lithium ions. This helps improve energy transfer rates and prevent dendrites’ formation in the electrolyte (Lim et al., 2024; Paleja, 2024).

**Nuclear Batteries**

Sinha (2024) discusses the UK nuclear-powered diamond battery with a 5,700-year lifespan, which operates off of carbon-14’s short-range radiation. The carbon-14 battery, encased in a diamond, produces electricity by safely capturing radioactive decay of carbon-14, a radioactive isotope commonly used in radiocarbon dating. Uses of the diamond battery, which could last for decades, include healthcare and space missions, where the use of traditional batteries which need frequent replacements is antithetical. The diamond battery is bio-compatible, meaning it could be used in healthcare to reduce patient discomfort and surgical risks, in uses such as powering implants including pacemakers, hearing aids, and ocular devices. The diamond batteries are also ideal for space missions and remote Earth locations to reduce costs and extend operational lifespans, and could power spacecraft, satellites, and even radio frequency (RF) tags. Chinese scientists developed a micronuclear battery with a photovoltaic cell that harnesses alpha rays released by decaying radioactive isotopes. The lifespan of this nuclear battery is hundreds of years, with a thousand times the efficiency of those using beta radiation (Li et al., 2024).

**Vanadium Batteries**

The completion of the project demonstrates the viability of large-scale vanadium flow battery systems for long-duration applications. Vanadium flow batteries are a promising technology for storing renewable energy, as they have long lifespans, high safety, and scalability. However, they also have a high initial cost, which limits their widespread adoption. The key component of a vanadium flow battery is the stack, which consists of a series of cells that convert chemical energy into electrical energy. The cost of the stack is largely determined by its power density, which is the ratio of power output to stack volume. The higher the power density, the smaller and cheaper the stack. Vanadium flow batteries provide continuous energy storage for up to 10+ hours, ideal for balancing renewable energy supply and demand. As per the company, they are highly recyclable and adaptable, and can support projects of all sizes, from utility-scale to commercial applications (Bhardwaj, 2024).

The durability, temperature resilience, and long-duration storage capacity of vanadium flow batteries suggests they could play a vital role in reducing the use of fossil fuels in power generation, particularly in harsh environments and remote locations (Carroll, 2024).

**Nickel-Hydrogen Batteries**

Li-ion batteries are vulnerable to thermal runaway, and in order to avoid a serious accident, big energy storage solutions require extra cooling, ventilation, and fire suppression facilities.

Nickel-hydrogen batteries may be used to replace lithium-ion batteries in big energy storage units because they have less risk of thermal runaway. Nickel-hydrogen batteries operate like traditional batteries with stacked electrodes, but they are enclosed in a pressurized gas tank. The cathode uses nickel hydroxide, while the anode relies on hydrogen. Charging produces hydrogen gas, which is oxidized during discharge to create water. Despite concerns about handling combustible hydrogen and pressurized tanks, the internal pressure is only 5 percent of that in hydrogen fuel cells. Additionally, any excess pressure causes hydrogen to recombine into water, ensuring safety (Malayil, 2024).

NASA has used nickel-hydrogen batteries for systems such as the International Space Station (ISS) since the 1970s. Platinum catalysts, which were expensive, were used in the initial design. But in 2020, Yi Cui, a materials science professor at Stanford, created a less expensive substitute utilizing a nickel-molybdenum-cobalt alloy, opening up the technology for wider use.

Cui’s invention of an affordable nickel-molybdenum-cobalt alloy catalyst led to the founding of EnerVenue. EnerVenue’s battery packs, called ESVs, feature six-foot-long, six-inch-wide tanks capable of storing 3 kWh of energy. Unlike lithium-ion batteries, ESVs operate across a wide temperature range (-40°F to 140°F) without requiring additional safety measures. However, nickel-hydrogen batteries are costlier to manufacture and have lower energy density, necessitating more units to match lithium-ion outputs (Malayil, 2024).

In addition to their scalability, flexibility, and high performance, EnerVenue’s ESVs boast good safety credentials with no thermal runaway or propagation risk associated with lithium-ion technologies. The ESVs are also more recyclable than lithium-ion.

**Lead-acid Deep-cycle Batteries**

A common battery used in vehicles, lead-acid batteries are inexpensive and can provide high surge currents.

**Nickel-cadmium**

A durable battery that can withstand extreme temperatures and high discharge currents, nickel-cadmium batteries are often used in power tools. Before rechargeable lithium batteries gained popularity, most rechargeable batteries were nickel-cadmium (NiCad). NiCad batteries use nickel oxide hydroxide and metallic cadmium as electrode materials. While not entirely obsolete yet, NiCad batteries are becoming less popular as lithium batteries take over the rechargeable battery market.

**Alkaline Batteries**

Additionally, the most common types of off-the-shelf batteries found in stores are alkaline batteries. Most of the AA and AAA batteries in use today are alkaline batteries that use zinc and manganese dioxide for the chemical reaction to store energy.

**Nickel metal hydride**

A rechargeable battery with a chemical reaction at the positive electrode similar to nickel-cadmium batteries.

**Proton Batteries**

Australian researchers have developed a new proton battery that could potentially replace lithium-ion batteries, which uses protons instead of lithium, using a novel organic material called tetraamino-benzoquinone (TABQ). TABQ facilitates the rapid movement of protons, which power the battery. Benefits of the battery include quick energy storage, extended cycle life, and efficient operation even in sub-zero temperatures, and could be used in applications such as grid-scale storage and electric vehicles (Zaremba, 2024).

**Zinc-Sulfur Batteries**

Aqueous Zinc-sulfur batteries use abundant and inexpensive materials, making them a greener and more affordable option, and offer the potential to power a wide range of applications, from renewable energy systems to portable electronics. Challenges facing zinc-sulfur batteries include zinc-anode corrosion, low conductivity, and dendrite growth. In their experiment, Guo et al. (2024) incorporated two essential additives into the battery: propylene glycol methyl ether and zinc iodide, which increased the battery’s ability to store and release energy by 20%. Inclusion of the additives also increased conductivity and stability and suppressed dendrite growth. Dendrites are tiny, needle-like structures that can form on the anode, and dendrite formation can lead to short circuits, battery failure, and potentially a fire. Zinc-sulfur batteries offer cost and safety advantages, and also the higher energy density enables smaller, longer-lasting devices, ideal for renewable energy and reliable applications (Guo et al., 2024; Dixit, 2024A).

**Zinc-ion Batteries**

In order to get aqueous zinc-ion batteries to endure several hundred thousand charge and discharge cycles, Lei et al. (2024) developed a special protective layer for the zinc anodes of the batteries, using a porous organic polymer called TpBD-2F to form a “stable, extremely thin and highly ordered film” on the zinc anode, which allows the zinc ions to flow very efficiently through nano-channels and at the same time keeps water away from the anode. “This layer addresses previous issues such as the growth of needle-like zinc structures — known as zinc dendrites — as well as unwanted chemical side reactions that trigger hydrogen formation and corrosion,” the research team explained in the statement. “Zinc-ion batteries with this new protective layer could replace lithium-ion batteries in large-scale energy storage applications, such as in combination with solar or wind power plants. They last longer, are safer, and zinc is both cheaper and more readily available than lithium,” said Da Lei, Ph.D. student and lead author of the research paper (Lei et al., 2024; Hannen, 2024).

**Sand Batteries**

A Finnish company is developing a 100-hour, sand-based storage system that will use crushed soapstone, a by-product from a fireplace manufacturer, as its storage medium. The new Sand Battery in Pornainen will be filled with crushed soapstone, a by-product of Tulikivi’s heat-retaining fireplace production. A total of 2,000 tons of soapstone will be used in the Sand Battery, equivalent to the weight of about a thousand soapstone fireplaces (Maisch, 2024D).

**Thermal Batteries**

Storing energy as heat can be cheaper, safer, and more convenient than storing it in traditional batteries, such as lithium or sodium. Thermal energy storage could boost wind and solar generation, and provide electricity to industries which have high temperature requirements. Heat, or thermal, batteries store excess electricity as heat in materials like bricks or graphite, which can reach temperatures over 3,000 degrees Fahrenheit. Thermal batteries, in addition to concentrated solar collectors, are ideal for powering the manufacturing of heavy industry such steel, cement and chemicals. Unrefined raw materials, like bricks made from clay, are used; a pound of brick stores more energy than a pound of lithium-ion battery, at less than 10% of the cost. Challenges facing thermal batteries include high upfront investment and a lack of familiarity among industrial users (Setyon, 2024).

Another option for thermal energy storage is storing the energy in water, enough to fill three Olympic-sized pools, and containing all the heat that water holds. A water thermal battery can be charged with hot water in the fall to help heat buildings on its district heating system through the winter, and then In the spring, the battery is charged with cold water, and uses the stored "cold" to help provide air conditioning. Water-based thermal batteries can be used in manufacturing industries needing heat below 500 C. Water thermal batteries can also be used for space heating in district energy systems that serve many buildings. The Energy Innovation Report by Axios suggests that thermal batteries could make industrial heating costs using electricity competitive with natural gas, while displacing 75 percent of fossil fuels burned for heat by U.S. industry. A 2020 report from the International Renewable Energy Agency (IRENA) expected the global market for thermal energy storage to triple by 2030, to 800 gigawatt hours. According to CSIRO, Australia's national science agency, thermal energy storage will be roughly a third cheaper than both lithium-ion batteries and pumped hydro for storage longer than four hours by 2050 (Chung, 2024).

**Thermal Battery**

1. Heat up a material, such as water or other substances that get much hotter, including graphite, sand or molten salt, up to 1,700 C.
2. Store it in a way that minimizes heat loss, such as in an insulated container, or underground.
3. Remove or transfer the heat to something like air or water for distribution when it's needed.

**Dual Use, Heat or Electricity**

1. The heat can be used to generate steam and turn turbines to generate electricity.
2. Used directly for space or water heating.
3. Industrial manufacturing.

Thermal batteries can store solar power in the form of heat for heating and cooling applications, as well as for producing domestic hot water, while maximizing self-consumption. “The French FHE system uses a solid-gas sorption system and operates without compressors,” Iacono said, noting that it also utilizes two thermal storage units and one storage tank. “Its core component is a solid-gas sorption technology that relies on a thermochemical reaction between a solid material and ammonia, which is a natural refrigerant with near-zero global warming potential,” he went on to say. This reaction absorbs or releases heat depending on the cycle phase, enabling efficient thermal storage and energy retrieval.” The system is composed of a hermetically sealed sorption module without moving parts, a heat exchanger for thermal transfer, and advanced control systems for predictive maintenance and seamless integration with renewable energy sources (Bellini, 2024).

Australian researchers have discovered a new thermal energy storage system material for the Carnot battery, which converts electrical energy into thermal energy for storage and back into electricity, as the newly discovered material integrates three modes of energy storage, creating a "trimodal" system that stores thermal energy. “The material, a mixture of boric and succinic acids, undergoes a transition at around 150°C and can store a record-breaking 600 MJ per $m^{3}$ of energy, which is almost two times higher than many existing materials. In this design, the new material acts as the key component in storing the thermal energy, withstanding more than 1,000 heating and cooling cycles, demonstrating excellent stability and performance over time.” This new material stores energy through three mechanisms simultaneously. First, it stores sensible heat as it warms up, then, during melting of the mixture, the boric acid undergoes a chemical reaction that further stores energy. Remarkably, the chemical reaction is highly reversible, allowing the material to be used repeatedly without degradation, a breakthrough in thermochemical TES materials. Boric acid, a flame-retardant substance derived from boron ores, and succinic acid, a bio-based chemical, are more low-cost and environmentally friendly than current lithium battery technology.

Molecular solar thermal (MOST) energy storage is a method for storing solar energy similar to a heat battery but comprising a large number of synthetically-created molecules, as the MOST molecules undergo structural changes on contact with sunlight, a process known as photo-induced reaction. The structural change sees the molecules absorb energy under the influence of light, which can be released again later as the molecules possess an on-off switching, which leads to them being referred to as photoswitches. German researchers are investigating three types of photoswitches in the Formost project: norbornadienes, azaborines, and azobenzenes. All three of these photoswitches switch from their ground state to a higher-energy storage state when exposed to light, thus changing their molecular structure and in some cases also their color. MOST molecules, which consist largely of carbon, oxygen, nitrogen and hydrogen, have several advantages, as all the chemical steps – conversion, storage and release of energy – are united in a single molecule. The molecules, which must be activated to release heat, enable energy to be delivered on demand, whereas the system, entirely CO2-neutral through storage, conversion, and release, allows heat to be stored for weeks or months as needed (Jowett, 2024).

**Ice Storage**

Project IceBrick is designed to provide customers with efficiency as a service by freezing a water-based solution during hours when electricity supply is at its most abundant and clean. The IceBrick system stores and later uses the ice to support cooling of the building during hours of peak demand, when the power grid faces highest demand. The IceBrick systems use Nostromo’s Cirrus software platform to operate as a VPP by orchestrating multiple energy assets to function together or as individual assets. VPPs are aggregations of electrified, grid-connected devices, including grid interactive efficient buildings. They reduce utilities’ reliance on natural gas peaker plants and the strain on transmission and distribution infrastructure by time-shifting cooling loads to shave electricity demand from times of peak usage, when electricity is most carbon-intensive (Fischer, 2024).

**Geothermal Energy**
Superhot rock, located 6 miles beneath the Earth’s surface and with temperatures exceeding 374 degrees Celsius (705.2°F), as opposed to typical geothermal energy which harnesses heat from the Earth’s surface, could also be a renewable energy source. Geothermal energy is typically harvested from areas with high heat flow near the Earth’s surface, such as near tectonic plate boundaries, and can be used to generate electricity or produce hydrogen. “Geothermal energy is an inexhaustible, always-available source of clean energy, and superhot rock energy could have the potential to provide long-term, scalable, renewable baseload power in many more places around the world at a scale and cost equivalent to fossil fuels.” To harvest superhot rock systems, wells are drilled 6 miles deep, and then water is injected into these hot rocks, heated, and then returned to the surface as steam. To conduct an effective geothermal project, detailed information is needed about temperature, stress, water flow, and rock properties, which can change as the system operates. Even though we have existing technologies from geothermal and oil and gas industries, in order to reduce risks and improve efficiency significant advancements are needed in drilling equipment and techniques. According to the study, superhot rocks can develop interconnected fractures, with these fractures allowing water to flow through them and reach extremely high temperatures, exceeding 400°C (752°F), transforming it into a supercritical state (Dixit, 2024B; Clean AIr Task Force, 2024).

**Batteries for Large-Scale Power Storage**

Today’s dominant energy storage chemistry is lithium iron phosphate (LFP) batteries. Giant lithium-ion batteries, the variety found in electric cars and cell phones, are being adapted to the electric grid. The most common utility-scale lithium-ion battery stores power for about four hours, enough to push through, for instance, an evening peak demand period after solar plants have largely stopped producing. To be truly useful, batteries need to be able to hold power for days, not hours.

***Energy Storage Strategies***

1. Pumped Storage Hydropower- In this system, excess energy produced during peak production periods – such as mid-afternoon on a solar-driven grid – is used to pump water up an incline to a reservoir. When energy is needed, the water is released to flow back downhill, creating electricity by spinning a turbine.
2. Thermal energy storage – A material, such as sand, is heated with excess power and then stored. When needed, the hot material is used to pressurize a gas, which then spins a turbine.
3. Alternative chemistry batteries – Alternative materials are used to construct a battery that stores power for longer or more cheaply than traditional lithium-ion batteries.
4. Gravity storage – Something heavy, such as sand or blocks of concrete, is lifted when energy is plentiful and then dropped during times of need, creating power through regenerative braking. Researchers have proposed repurposing existing mines for this type of storage.
5. Compressed air storage – Excess power is used to pump and compress air in underground chambers, which is released to spin a turbine when needed.
6. Hydrogen fuel – Excess renewable energy is used to split hydrogen from water, which can then be transformed into electricity by a fuel cell.



*Department of Energy/ Water Power Technologies Office*

**Magnesium-Ion Batteries**

Magnesium-ion batteries offer a safe, low-cost, and high-energy density alternative to current lithium-ion batteries. The advanced electrolyte development strategy presented in our research holds potential beyond magnesium-ion batteries, extending to other multivalent metal ion batteries, such as zinc-ion and aluminum-ion batteries (Leong et al., 2023; Maisch, 2023A).

***Challenges with Magnesium-Ion Batteries***

1. Need to overcome the narrow electrochemical window in aqueous systems
2. Poor ionic conductivity in non-aqueous systems

***Advantages of this Design***

1. Offers the high voltage of non-aqueous systems
2. Offers the safety and cost-effectiveness of aqueous systems

Researchers at the University of Hong Kong (HKU) have developed a quasi-solid-state magnesium-ion battery with a voltage plateau at 2.4 V and an energy density of 264 Wh/kg. It surpasses the performance of current magnesium-ion batteries and almost matches the performance of lithium-ion batteries. In extensive cycling tests, the research team found that even under extreme conditions of subzero temperatures (-22°C), the quasi-solid-state magnesium-ion battery retained 90% of its capacity after 900 cycles. The battery is also non-flammable and resistant to high pressure loading, which makes it a promising candidate for consumer electronics, even in colder climates (Leong et al., 2023; Maisch, 2023A).

The same research team previously developed a water-in-salt magnesium-ion battery with an operating voltage above 2 V, yet, it still lagged behind non-aqueous counterparts due to the dominance of proton over Mg-ion storage in the cathode. They improved on the earlier design by implementing a polymer-enhanced electrolyte to control the competition between protons and metal ions and confine the hydrogen bond network. Hydrogen ions, or protons, are smaller and lighter compared to the metal ions. Because of their size, protons can easily get into the battery's cathode structure. However, this creates a problem because protons and magnesium ions compete for space, which severely limits how much energy the battery can store and how long it can last (Leong et al., 2023; Maisch, 2023A).

**Dyness, China, Lithium Iron Phosphate Batteries**

China’s Dyness says its new 312 kWh storage system uses 375 Ah lithium iron phosphate batteries. It also claims that its cooling system reduces average temperature increases by 6 C. The new commercial battery with a system capacity of 312 kWh, the DH300Y system uses LFP batteries with a cell capacity of 375Ah, and it includes one cluster of five battery packs. The system uses liquid and air for cooling, and it utilizes digital intelligence to achieve the leveling of temperature rise and reduce the average temperature rise by 6℃. “The daily power saving of its single machine can reach 6kWh,” the company added. “In addition, DH300Y can increase the battery efficiency to 96%. This can shorten the project payback period and increase the return on investment by up to 6% in case of effective application.” The product sheet for the battery states that 10 separate battery systems can be connected in parallel, and each unit comes at a weight of 3,200 kg, a width of 1.5 meters, and a height of 2.5 meters. The system can further be connected to the internet for remote operation and maintenance. “The new product applies active safety technologies such as Pack core pressure sensing, real-time insulation detection, and active exhaust, as well as safety initiatives such as three-stage fire protection, three-stage fusing, passive explosion-proof devices, and all-around double-layer flame-retardant structural design, to safeguard the stability of the electric cores and the system with multiple safety guarantees,” the company added (Kahana, 2023B).

**ZYC Energy, China, Lithium Iron Phosphate Batteries**

Chinese manufacturer ZYC Energy says its new LiFePo4 battery has a lifecycle of more than 6,000 cycles, comes with a 10 year warranty, and is designed for off-grid and residential applications. The DIY 5000 system measures 440 mm x 134 mm x 480 mm and weighs 46 kg. It features a capacity of 5.12 kWh and a nominal voltage of 51.2 V. The nominal voltage is between 40 V and 58.4 V and the maximum continuous current is 100 A. Discharge ambient temperatures range between -20 C and 55 C. The system can be scaled up combining up to 64 units, thus reaching a storage capacity of 327.6 kWh. ZYC Energy, which is based in China's Guangdong province, offers two size options for combination cabinets, either for six units or for 10 units in a parallel configuration (Bellini, 2023I).

**Lithium Metal Batteries**

Lithium metal batteries have the potential to replace lithium-ion batteries, as batteries with better performance are needed to upgrade the electric grid. The use of lithium metal as the anode for batteries results in better energy density than other materials, replacing the graphite anode in lithium-ion batteries. However, the Li metal anode is unstable and readily reacts with electrolyte to form a solid-electrolyte interphase (SEI). Unfortunately, the natural SEI is brittle and fragile, resulting in poor lifespan and performance. ASEI: artificial solid electrolyte interphase is the answer that can make lithium metal batteries viable, including polymeric ASEI layers and inorganic-organic hybrid ASEI layers. Polymeric layers also have similar functional groups as electrolytes which makes them extremely compatible; this compatibility is one of the major areas other components lack. Inorganic-organic hybrid layers are best for their reduction in layer thickness and marked improvement over the distribution of components within the layers, which improves the overall performance of the battery (Wang et al., 2023; Tsinghua, 2023).

The anode, lithium metal, is reactive with electrolyte and a passivation layer, called a solid-electrolyte interphase, forms on the surface of lithium metal during battery operation. Another issue of lithium metal anode is so called "dendrite growth", appearing during battery charging. Dendrites look like tree-branch structures that cause internal damage to the battery, leading to short-circuiting, poor performance, and potential safety hazards. These weaknesses altogether reduce the practicality of LMBs and pose some challenges that must be addressed. To improve upon the lithium metal anode, the researchers found it is necessary to homogenize the distribution of lithium ions, which can help reduce the deposits on negatively charged areas of the batteries. This, in turn, will reduce the dendrite formation which can prevent premature decay and short-circuiting. Additionally, creating an easier way for the lithium ions to diffuse while also ensuring the layers are electrically insulated can help retain the integrity of the structure, both physically and chemically, during battery cycling. Most importantly, reducing the strain between the interface of the electrode and electrolyte can ensure proper connectivity between the layers, which is an essential part of the functionality of the battery (Wang et al., 2023; Tsinghua, 2023).

Research areas for lithium metal batteries include improvement in the adhesion of the ASEI layers on the surface of the metal, which overall improves the function and longevity of the battery. Also, stability in the structure and chemistry within the layers, as well as minimizing the thickness of the layers to improve the energy density of the metal electrodes (Wang et al., 2023; Tsinghua, 2023).

**Phosphorous Nanoribbons**

Researchers at University College London have developed one-atom-thick ribbons composed of a phosphorus and arsenic alloy. This breakthrough material holds the potential to significantly enhance the performance of various devices including batteries, supercapacitors, and solar cells. However, phosphorus-only materials do not conduct electricity very well, hindering their usage for certain applications. In a study published in the *Journal of the American Chemical Society*, the researchers created nanoribbons made of phosphorus and tiny amounts of arsenic, which they found were able to conduct electricity at temperatures above -140 C, while retaining the highly useful properties of the phosphorus-only ribbons (Zhang, F.F., et al., 2023; UCL, 2023).

In 2021 it was shown that adding the nanoribbons as a layer to perovskite solar cells allowed the cells to harness more energy from the Sun. The arsenic-phosphorus ribbons have also turned out to be magnetic which we believe comes from atoms along the edge, which makes them potentially of interest for quantum computers too. To be used as an anode material in lithium-ion or sodium-ion batteries, phosphorus nanoribbons currently would need to be mixed with a conductive material like carbon. By adding arsenic, the carbon filler is no longer necessary and can be removed, enhancing the amount of energy the battery can store and the speed at which it can be charged and discharged. In solar cells, meanwhile, arsenic-phosphorus nanoribbons can further improve the flow of charge through the devices, enhancing the cells’ efficiency (Zhang, F.F., et al., 2023; UCL, 2023).

The arsenic-phosphorus ribbons created by the research team were typically a few layers high, several micrometers long, and tens of nanometres wide. They were made by mixing crystals formed from sheets of phosphorus and arsenic with lithium dissolved in liquid ammonia at -50 degrees C. (After 24 hours, the ammonia is removed and replaced with an organic solvent.) The sheets’ atomic structure means the lithium ions can travel in one direction only, not laterally, causing cracking that creates the ribbons. A key characteristic of the nanoribbons is that they also have extremely high “hole mobility”. Holes are the opposite partners to electrons in electrical transport, so improving their mobility (a measure of the speed at which they move through the material) helps electrical current move more efficiently (Zhang, F.F., et al., 2023; UCL, 2023).

**Salt Batteries**

Research into salt for heat storage has increased in recent years, as salt batteries can store summer heat to use during winter, with many different types of salts to choose from. Solar panels convert light from the sun into energy, but the solar panels also are heated by the sun, as this heat can be stored with salt batteries. Lian Blijlevens of Radboud University said, “The heat can be extracted by a solar boiler and used to heat your house or shower. However, in summer you always generate more solar heat than you use, and in winter you have less. So what we need is a way to preserve that heat (Radboud University, 2023).”

The chemistry of salt batteries has long been known, but what is still being researched is which salts are really suitable for use in homes. "A salt battery contains salt hydrates, which are salts with water in the crystals. The battery recharges by heating the salt, which causes the water to go out of the crystals. When you need the heat, you add water vapor to the crystals and the heat is released again," says Blijlevens. "If you want to heat a house this way, you need about 10 $m^{3}$ of material, which corresponds to two to three wardrobes. You no longer need natural gas and you can use the heat you store in summer in winter. It's a great solution to a major problem (Radboud University, 2023)."

**Procedure**

1. Assess hundreds of salts on availability, safety, and compactness
2. The dozen or so salts that made it through the initial assessment are then tested in the lab for recyclability. You don't want to have to replace the salt every year
3. Test the salts using thermal analysis: place the salt on heated scales and increase the temperature. You can see the weight of the salt change, which shows that the water is evaporating out of it. If you then add water vapor again at a lower temperature, you can see how much water is being absorbed.

**Types of Salt**

1. Strontium Chloride: not too expensive, heats up well, and remains stable without side effects
2. Potassium Carbonate: is cheaper, but this salt also reacts to CO2, which makes the battery less effective in the long run

**Sodium-Ion Batteries**

In 2023, Swedish battery maker Northvolt developed its first sodium-ion battery in partnership with Uppsala University spinoff Altris. The cell was validated for an energy density of more than 160 Wh/kg and is designed primarily for energy storage applications. Today’s dominant energy storage chemistry is lithium iron phosphate (LFP) batteries. The Northvolt battery has a sodium-ion cell which is based on a hard carbon anode and a Prussian White-based cathode, which makes it similar to the first generation of sodium-ion cells unveiled by Chinese battery industry heavyweight CATL in 2021. CATL also uses layered oxide cathodes. Northvolt, on the other hand, has adhered to nickel-manganese-cobalt (NMC) battery chemistry, which is favored by electric-vehicle customers. The company's ESS platform is based on the same chemistry, which is seen as less sustainable than LFP due to cobalt and nickel content (Maisch, 2023B).

The two battery technologies have much in common in terms of structure and working principles and can often even use the same manufacturing lines and equipment. However, sodium-ion offers superior environmental credentials, enhanced safety, and better raw material costs than lithium-ion. Generally, Na-ion cells are quoted to be even up to 40% cheaper, but the challenge is bringing the technology to scale (Maisch, 2023B).

Bush, Steve (2025) Electronics, Weekly, Eliminating another flaw in sodium-ion batteries <https://www.electronicsweekly.com/news/research-news/another-flaw-in-sodium-ion-batteries-eliminated-2025-01/>

Zuo, W., Gim, J., Li, T. et al. (2024) Microstrain screening towards defect-less layered transition metal oxide cathodes, Nature Nanotechnology 19, 1644–1653, <https://doi.org/10.1038/s41565-024-01734-x>

U.S. researchers at Argonne studied cracking rates in sodium-ion oxide cathodes made from transition-metal core-shell particles, a nickel-rich core surrounded by a cobalt and manganese-rich shell. “The manganese-rich surface gives the particle its structural stability during charge-discharge cycling,” according to the lab. “The nickel-rich core provides high capacity for energy storage.” Energy storage capacity steadily declined during cycling, which was narrowed down to cracks developing in the cathode particles due to strain arising between the shell and core in the particles. These cracks were initiated deep within the particles, and not, as had been expected, at the surface, and consequently crack-proof cathode particles were produced by heating at 1°C/minute. Core-shell cathode particles are made by heating hydroxide precursors at temperatures up to 600°C. With a warming rate of 5°C/minute cracks initiated at the core and the core-shell boundary at as little as 250°C, while heating unusually slowly – at 1°C/minute – produced robust particles (Zuo et al., 2024; Bush, 2025).

**Solid-State Batteries**

In the effort to achieve lighter, cheaper and faster charging electric vehicles, solid-state batteries have been proposed as one solution. A solid state battery is different from a lithium-ion battery because of a component known as the electrolyte. In a lithium-ion battery, the electrolyte is a gooey liquid, whereas in a solid state battery, the electrolyte is a solid. That solid electrolyte is one reason that solid state batteries might be safer than lithium-ion batteries. If a liquid electrolyte battery is broken or punctured, the two sides of the electrolyte can ooze together, which can lead to an uncontrolled energy flow, followed by a fire. Solids are also denser than liquids meaning the electrolyte takes up less space and battery cells can be smaller. Fast-charging times is one area of research for solid-state batteries, as it generally takes the lithium ions in batteries more time to move through a rigid material than a liquid. That tends to make it take longer to receive energy, which slows charging times, and makes it slower to release energy — which drags on a vehicle’s acceleration. Solid-state batteries will also tend to be more expensive because they contain more lithium (Valdes-Dapena, 2023).

**Sodium-Sulfur Batteries**

Sulfur based alkali-metal batteries using liquid sulfur for the positive electrode and a [ceramic](https://en.wikipedia.org/wiki/Ceramic) tube of [beta-alumina solid electrolyte](https://en.wikipedia.org/wiki/Beta-alumina_solid_electrolyte) (BASE), include the [sodium–sulfur battery](https://en.wikipedia.org/wiki/Sodium%E2%80%93sulfur_battery) (NaS battery) and the [lithium–sulfur batter](https://en.wikipedia.org/wiki/Lithium%E2%80%93sulfur_battery)y. In sulfur-based batteries, Insulator corrosion can become a problem because they gradually become conductive, and the self-discharge rate increases.

NaS batteries can be used for space applications because of their high specific power. An NaS battery for space use was successfully tested on the [Space Shuttle](https://en.wikipedia.org/wiki/Space_Shuttle) mission [STS-87](https://en.wikipedia.org/wiki/STS-87) in 1997,[[9]](https://en.wikipedia.org/wiki/Molten-salt_battery#cite_note-venus-9) but the batteries have not been used operationally in space. NaS batteries have been proposed for use in the high-temperature environment of [Venus](https://en.wikipedia.org/wiki/Venus).[[9]](https://en.wikipedia.org/wiki/Molten-salt_battery#cite_note-venus-9)

Commercial NaS battery bank

* Capacity : 25–250 kWh per bank
* Efficiency of 87%
* Lifetime of 2,500 cycles at 100% depth of discharge (DOD), or 4,500 cycles at 80% DOD

Brahambhatt, Rupendra (2025) Interesting Engineering, Sodium-sulfur battery breakthrough retains 81% capacity after 200 cycles, <https://interestingengineering.com/energy/new-electrolyte-for-sodium-sulfur-batteries>

Sodium Sulfur Batteries, <https://www.sciencedirect.com/topics/materials-science/sodium-sulfur-battery#:~:text=Sodium%2Dsulfur%20batteries%20have%20unique,and%20convenient%20maintenance%20%5B59%5D>.

Huang, J., Song, Z., Wu, J., et al. (2024) In situ polymerized quasi-solid polymer electrolytes enabling void-free interfaces for room-temperature sodium–sulfur batteries, Energy Materials and Devices, Volume 2, Issue 4, <https://www.sciopen.com/article/10.26599/EMD.2024.9370051>

While lithium makes up only 0.002 percent of Earth’s crust, sodium accounts for more than 2.5 percent. It is more abundant and environment-friendly compared to lithium.

Na-S batteries could cost less, offer high energy density, be lightweight, require less water during production, withstand high-temperature conditions, and potentially have longer lifespans than conventional batteries. Current sodium-sulfur battery designs suffer from poor conductivity, low efficiency, and various safety issues. The root cause of these problems is the unstable electrode-electrolyte interfaces. For instance, the typical electrolyte used in Na-S batteries is molten sodium beta-alumina solid electrolyte (BASE). This electrolyte is unable to prevent the formation of sodium dendrites, pointed microscopic structures that cause short circuits. Moreover, BASE also fails to limit the activity of sodium polysulfide, a byproduct formed as a result of the reaction between sodium and sulfur. This byproduct keeps moving back and forth between the two electrodes, reducing battery performance and capacity (also called the polysulfide shuttling effect). DS-QSPE. They claim that this electrolyte can “effectively stabilize the electrode/electrolyte interfaces and suppresses the polysulfide shuttle effect in room-temperature Na-S batteries.” DS-QSPE is a quasi-solid polymer electrolyte which means that it combines the properties of both solid and liquid electrolytes. Such an electrolyte is typically made by incorporating a liquid electrolyte into a polymer matrix, resulting in a gel-like or semi-solid material (Huang et al., 2024; Brahambhatt, 2025).

**Sodium-Nickel Chloride Batteries**

The ZEBRA "Zero Emissions Batteries Research Activity") battery uses NaNiCl2 with Na+-beta-alumina ceramic electrolyte (Shukla and Martha, 2001). The NaNiCl2 battery operates at 245 °C (473 °F) and uses molten [sodium tetrachloroaluminate](https://en.wikipedia.org/wiki/Sodium_tetrachloroaluminate) (NaAlCl4) for the electrolyte, which has a melting point of 157 °C (315 °F). The negative electrode is molten sodium in a sodium-nickel chloride battery. The positive electrode is [nickel](https://en.wikipedia.org/wiki/Nickel) in the discharged state and [nickel chloride](https://en.wikipedia.org/wiki/Nickel_chloride) in the charged state. Because nickel and nickel chloride are nearly insoluble in neutral and [basic](https://en.wikipedia.org/wiki/Alkaline) melts, contact is allowed, providing little resistance to charge transfer. Since both NaAlCl4 and Na are liquid at the operating temperature, a sodium-conducting [β-alumina ceramic](https://en.wikipedia.org/wiki/Beta-alumina_solid_electrolyte) is used to separate the liquid sodium from the molten NaAlCl4. Nickel and chloride have much higher worldwide reserves and annual production than lithium (Tahil, 2006).

Na-NiCl2 batteries are typically kept molten when not in use because if allowed to solidify they typically take twelve hours to reheat and charge (Jung et al., 2018). Factors that influence reheating time include the battery-pack temperature, and power available for reheating. The amount of insulation influences how fast a ZEBRA battery can cool and solidify, typically 5-7 days, as after shutdown a fully charged battery pack loses energy. Sodium metal chloride batteries suitable for the industrial and commercial energy storage installations, as they are safe and can also be installed outdoors without cooling systems. A [thermal runaway](https://en.wikipedia.org/wiki/Thermal_runaway) can be activated only by piercing the battery, and in this unlikely event no fire or explosion will be generated, so sodium metal chloride batteries are generally safe.

**Liquid-Metal Batteries**

Liquid-metal rechargeable batteries can use either magnesium–antimony and more recently [lead–antimony](https://en.wikipedia.org/wiki/Lead%E2%80%93antimony). The electrode and electrolyte layers are heated until they are liquid and self-segregate due to density and [immiscibility](https://en.wikipedia.org/wiki/Immiscibility). In liquid-metal batteries, the electrodes go through a cycle of creation and destruction during the charge–discharge cycle, which makes them immune to the degradation that afflicts conventional battery electrodes; thus, liquid-metal batteries can have longer lifetimes than conventional batteries (Kim et al., 2012). M[agnesium](https://en.wikipedia.org/wiki/Magnesium) and [antimony](https://en.wikipedia.org/wiki/Antimony) can be separated by a molten salt in a liquid-metal battery (Chandler, 2009). Magnesium is used as the negative electrode for its low cost and low solubility in the molten-salt electrolyte, and antimony is used as the positive electrode due to its low cost and higher anticipated discharge voltage. In 2011, researchers demonstrated a liquid-battery cell with a lithium anode and a lead–antimony cathode, which had higher ionic conductivity and lower melting points (350–430 °C). A drawback of the Li chemistry is higher cost (Kim e al., 2012). A PbBi alloy enables a lower melting point lithium-based battery. It uses a molten salt electrolyte based on LiCl-LiI and operates at 410 °C (Kim et al., 2018). Ionic liquids have been shown to have prowess for use in rechargeable batteries. The electrolyte is pure molten salt with no added solvent, which is accomplished by using a salt having a room temperature liquid phase. This causes a highly viscous solution, and is typically made with structurally large salts with malleable lattice structures (Giffen, 2016).

**Non-rechargeable Thermal Batteries**

Thermal batteries are commonly found in military applications, including nuclear weaponsand [guided missiles](https://en.wikipedia.org/wiki/Guided_missiles). In these weapons grade thermal batteries, the electrolyte is immobilized when molten by a special grade of [magnesium oxide](https://en.wikipedia.org/wiki/Magnesium_oxide) that holds it in place by [capillary action](https://en.wikipedia.org/wiki/Capillary_action). A separator between the [anode](https://en.wikipedia.org/wiki/Anode) and [cathode](https://en.wikipedia.org/wiki/Cathode) of each cell in the battery stack is created by pressing a powdered mixture into [pellets](https://en.wiktionary.org/wiki/pellet). The thermal battery stays inert and remains inactive as long as the salt electrolyte remains solid. A pyrotechnic heat source is included in each battery cell, which is used to heat the cell to the typical operating temperature of 400–550 °C.

Thermal batteries provide high power for a short period of time, ranging from tens of seconds to 60 minutes, by using an electrolyte that is solid and inactive at ambient temperatures. This electrolyte can be stored indefinitely, around 50 years, and provides instant power when activated. They have an output ranging from [watts](https://en.wikipedia.org/wiki/Watt) to [kilowatts](https://en.wikipedia.org/wiki/Kilowatt), with the high power being due to the high [ionic conductivity](https://en.wikipedia.org/wiki/Conductivity_%28electrolytic%29) of the molten salt (resulting in a low internal resistance), which is three orders of magnitude (or more) greater than that of the [sulfuric acid](https://en.wikipedia.org/wiki/Sulfuric_acid) in a [lead–acid car battery](https://en.wikipedia.org/wiki/Lead%E2%80%93acid_battery).

***Thermal Battery Designs***

1. Edge- A fuze strip (containing [barium chromate](https://en.wikipedia.org/wiki/Barium_chromate) and powdered [zirconium](https://en.wikipedia.org/wiki/Zirconium) metal in a ceramic paper) along the edge of the heat pellets to initiate the electrochemical reaction. Battery activation is achieved with an [electrical igniter](https://en.wikipedia.org/wiki/Electric_match) or [squib](https://en.wikipedia.org/wiki/Squib_%28explosive%29) which is activated with an electric current. This design has an activation time of hundreds of milliseconds.
2. Central Hole- A central hole in the middle of the battery stack, into which the high-energy electrical igniter fires a mixture of hot gases and [incandescent](https://en.wikipedia.org/wiki/Incandescent) particles. This design has a shorter activation time of tens of milliseconds. In this design, battery activation is accomplished with a [percussion primer](https://en.wikipedia.org/wiki/Percussion_primer), which is similar to a [shotgun shell](https://en.wikipedia.org/wiki/Shotgun_shell). The gasless heat source consists of mixtures of [iron](https://en.wikipedia.org/wiki/Iron) powder and [potassium perchlorate](https://en.wikipedia.org/wiki/Potassium_perchlorate) in weight ratios of 88/12, 86/14, or 84/16 (Koch, 2019). A higher heat output (nominally 200, 259, and 297 [cal](https://en.wikipedia.org/wiki/Calories)/[g](https://en.wikipedia.org/wiki/Gram) respectively) results from a higher potassium perchlorate level. The central hole design has unactivated storage, which both avoids deterioration of the active materials during storage, and eliminates capacity loss due to [self-discharge](https://en.wikipedia.org/wiki/Self-discharge) until the battery is activated.

The first generation of thermal batteries used [calcium](https://en.wikipedia.org/wiki/Calcium) or [magnesium](https://en.wikipedia.org/wiki/Magnesium) anodes, with cathodes of [calcium chromate](https://en.wikipedia.org/wiki/Calcium_chromate), [vanadium](https://en.wikipedia.org/wiki/Vanadium_pentoxide) or [tungsten oxides](https://en.wikipedia.org/wiki/Tungsten_trioxide). In the 1980s [lithium](https://en.wikipedia.org/wiki/Lithium)-silicon alloys anodes replaced calcium and magnesium anodes and lithium-aluminum alloys. The lithium-alloy anodes use [iron disulfide](https://en.wikipedia.org/wiki/Iron_disulfide) (pyrite) replaced by cobalt disulfide for high-power applications for the cathode. The electrolyte in thermal batteries is usually a [eutectic mixture](https://en.wikipedia.org/wiki/Eutectic_mixture) of [lithium chloride](https://en.wikipedia.org/wiki/Lithium_chloride) and [potassium chloride](https://en.wikipedia.org/wiki/Potassium_chloride), with eutectic relating to or denoting a mixture of substances (in fixed proportions) that melts and solidifies at a single temperature that is lower than the melting points of the separate constituents or of any other mixture of them.

Lower-melting, eutectic electrolytes based on [lithium bromide](https://en.wikipedia.org/wiki/Lithium_bromide), [potassium bromide](https://en.wikipedia.org/wiki/Potassium_bromide), and lithium chloride or [lithium fluoride](https://en.wikipedia.org/wiki/Lithium_fluoride) are better conductors and have thus been used to provide longer operational lifetimes. An all-lithium electrolyte which has ionic conductivity, of [lithium chloride](https://en.wikipedia.org/wiki/Lithium_chloride), [lithium bromide](https://en.wikipedia.org/wiki/Lithium_bromide), and [lithium fluoride](https://en.wikipedia.org/wiki/Lithium_fluoride) (no potassium salts). is used for high-power applications. A [radioisotope thermal generator](https://en.wikipedia.org/wiki/Radioisotope_thermal_generator), such as in the form of pellets of 90SrTiO4, can be used for long-term delivery of heat for the battery after activation, keeping it in a molten state.[[23]](#footnote-22)

Business Wire (2025) Microvast Announces Breakthrough in True All-Solid-State Battery Technology, <https://finance.yahoo.com/news/microvast-announces-breakthrough-true-solid-140000399.html>

improving safety, energy density, and efficiency for critical applications such as data center backup power systems and electric school buses, while also paving the way for future innovations in robotics and other high-demand sectors such as electric vehicles.

A voltage unattainable by any battery containing liquid electrolytes, which would otherwise decompose under such high voltages.

Microvast's ASSB utilizes a bipolar stacking architecture that enables internal series connections within a single battery cell. This bipolar design significantly reduces the number of interconnections between cells, modules, and packs. This simplifies the overall system architecture and enhances both energy efficiency and operational safety. Furthermore, Microvast has developed its proprietary all-solid electrolyte separator membrane based on an advanced polyaramid separator, which is non-porous and tailored specifically for solid-state applications. This separator ensures excellent ionic conductivity, structural stability, and long-term durability, addressing one of the most critical technical challenges in solid-state battery technology.

Science China Press (2025) SciTechDaily, Next-Gen Zinc-I2 Batteries: High Capacity Meets Long-Term Durability,

<https://scitechdaily.com/next-gen-zinc-i2-batteries-high-capacity-meets-long-term-durability/>

Chen, S., Ma, J., Chen, Q., et al. (2024) Exploring interfacial electrocatalysis for iodine redox conversion in zinc-iodine battery, Science Bulletin, DOI: 10.1016/j.scib.2024.11.042

Researchers developed a novel Zn-I₂ battery design using Zn-SA-MoC/NCFs to overcome iodine’s limitations, achieving high capacity (230.6 mAh g⁻¹) and durability (90% retention after 20,000 cycles). Aqueous zinc-ion batteries (ZIBs) have gained significant attention for their high safety, widespread availability of raw materials, and environmental compatibility. Iodine, which is abundant in seawater (55 μg L−1), holds great potential for use in zinc-iodine batteries due to its high theoretical capacity (211 mAh g−1) and suitable redox potential (0.54 V). However, iodine’s low electrical conductivity limits efficient redox conversion during energy storage. Furthermore, the formation of soluble polyiodides can migrate to the zinc anode, causing capacity degradation and zinc corrosion.

To address the existing issues in Zn-I2 batteries, the research team presents the precipitation method to encapsulate molybdate ions into zeolitic imidazolate framework-8 (ZIF-8), followed by electrospinning and calcination to create free-standing porous carbon fibers with Zn single atom sites and molybdenum carbide clusters (Zn-SA-MoC/NCFs). With the hierarchical porous carbon framework for favorable mass transfer, the integration of molybdenum carbides with single-atom catalysts is expected to amplify the adsorption capability to iodine species and modulate the catalytic activity with an optimal charge redistribution. Thus, the assembled Zn-I2 batteries demonstrate a large specific capacity of 230.6 mAh g−1 at a current density of 0.5 C (1 C= 0.211 mA cm−2) and the good capacity retention of 90% after 20,000 cycles.

Maisch, Marija (2025) PV Magazine, High-voltage, super-stable sodium–zinc hybrid batteries,

<https://www.pv-magazine.com/2025/01/24/high-voltage-super-stable-sodium-zinc-hybrid-batteries/?utm_source=Global+%7C+Newsletter&utm_campaign=ad886cc5b9-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-ad886cc5b9-160603208>

Kong, D., Wei, X., Yue, J., et al. (2024) Advanced high-voltage and super-stable sodium–zinc hybrid ion batteries enabled by a hydrogel electrolyte, Energy Materials and Devices, Volume 2, Issue 4, <https://www.sciopen.com/article/10.26599/EMD.2024.9370050>

Aqueous, non-lithium-based, rechargeable batteries are promising candidates for next-generation large-scale energy storage systems owing to their safety credentials and low cost. However, their commercialization is hindered by a narrow electrochemical stability window and relatively low energy density.

Researchers from the China University of Petroleum have synthesized a novel hydrogel electrolyte that, when paired with a Prussian blue cathode, achieves outstanding energy density and cyclability in sodium-zinc hybrid ion batteries. The newly developed hydrogel electrolyte, named Zn–SA–PSN, is built on a polymer network featuring interconnected amide chains and hydrophilic functional groups, which are key to its high performance. This design delivered an impressive ionic conductivity of 43 mS·cm⁻¹, significantly surpassing traditional electrolytes, and an expanded electrochemical stability window of 2.5 V. The broader stability window supports higher voltage operations, critical for enhancing the energy density of batteries.

When paired with a Prussian blue cathode, the sodium-zinc hybrid battery demonstrates remarkable performance, achieving over 6000 cycles with a minimal capacity decay of just 0.0096% per cycle at a high current density of 25 C. This stability is attributed to the hydrogel electrolyte’s ability to suppress side reactions and inhibit dendrite growth, which are common challenges in zinc anodes.

Maisch, Marija (2025) PV Magazine, New aluminum-ion battery with unprecedented long cycle life,

<https://www.pv-magazine.com/2025/01/29/new-aluminum-ion-battery-with-unprecedented-long-cycle-life/?utm_source=Global+%7C+Newsletter&utm_campaign=7f5382b038-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-7f5382b038-160603208>

Guo, K., Wang, W., Song, W., et al., (2024) A Recyclable Inert Inorganic Framework Assisted Solid-State Electrolyte for Long-Life Aluminum Ion Batteries, American Chemical Society, <https://doi.org/10.1021/acscentsci.4c01615>

The environmentally friendly and high-safety aluminum-ion batteries have attracted much interest, but the extensive use of expensive electrolyte, strong moisture sensitivity, and severe corrosion of the Al anode have limited their commercial application. However, conventional aluminum-ion batteries suffer from performance limitations and safety issues related to the use of liquid electrolytes. These electrolytes, typically composed of aluminum chloride, are corrosive to the battery’s components and highly sensitive to moisture. This can lead to a decline in performance over time and pose potential hazards.

Chinese researchers aluminum-ion batteries. They have created a solid-state electrolyte that facilitates the smooth movement of aluminum ions, significantly improving battery performance and longevity. The team added an inert aluminum fluoride salt to an Al-ion-containing electrolyte, turning it into a solid-state electrolyte. The aluminum fluoride salt has a 3D porous structure, allowing aluminum ions to easily hop across the electrolyte and increase conductivity. They also used fluoroethylene carbonate as an interface additive to create a thin solid coating on the electrodes to prevent the formation of aluminum crystals that degrade battery health. The newly developed aluminum-ion battery overcomes these hurdles by using a solid electrolyte. This approach enhances the battery’s stability and mitigates the corrosion issues associated with liquid electrolytes.

Willuhn, Marian (2025) PV Magazine, EMPA develops biodegradable fungi battery,

<https://www.pv-magazine.com/2025/01/27/empa-develops-biodegradable-fungi-battery/?utm_source=Global+%7C+Newsletter&utm_campaign=45ea69cbdd-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-45ea69cbdd-160603208>

Swiss researchers 3D-printed battery. Fungi are used as anode and cathode with one releasing electrons during metabolism and the other able to absorb them.

possible application for non-toxic power supply in simple measuring devices such as the temperature sensors used in agriculture or environmental research. After supplying temperature sensors with power for a few days, the organic batteries would decompose. the battery is a microbial fuel cell. The two types of fungi produce different enzymes and degradation products during metabolism. On the anode side there is a yeast fungus whose metabolism releases electrons. The cathode consists of white rot fungi – velvet trametes. The latter produces an enzyme that can capture the electrons from the yeast metabolism, the researchers claim. The battery is manufactured by 3D printing with the fungi mixed into the printer “ink.” The active components of the battery are, thus, structural components. “It is challenging enough to find a material in which the fungi grow well,” said Gustav Nyström, head of the Cellulose & Wood Materials laboratory at Empa. “But the ink must then also be easy to extrude without the fungal cells dying – and of course it should also be electrically conductive and biodegradable.” A cellulose-based ink met the requirements by providing nutrients for the fungi, making the device biodegradable. To ensure the battery does not degrade too quickly, the researchers added sugar molecules. Those are broken down by the fungus before the ink is metabolized. The cellulose structure, with the fungi and sugar molecules, is covered in beeswax and equipped with two copper contacts. For the battery to start generating electricity, the fungi need water. This means the device can be stored in a dried state without the mushroom metabolizing the sugar or ink. The battery is activated by adding water, said Nyström. The Empa team now wants to identify new fungi, materials, and inks to make the battery more compact and powerful, potentially expanding its application.

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